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Texas A and M Univ, College Station

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This report represents a comprehensive bibliography of recent systems analysis studies reported in the technical literature as applied to manufacturing systems. This annotated bibliography was compiled in the early stages of the GEMS project as an effort to categorize, summarize, and compare relevant systems analysis work in the operation, analysis, and scheduling of manufacturing systems. Particular emphasis was placed upon the application of digital simulation methodologies and job shop scheduling rules to manufacturing systems. This report is being reproduced and distributed in the hope that it might aid any engineer or manager interested in the application of systems analysis/operations research methodologies to manufacturing systems.

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Definition, Development, and Implementation
of a
Generalized Manufacturing Simulator; GEMS

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ABSTRACT

This report represents a comprehensive bibliography of recent systems analysis studies reported in the technical literature as applied to manufacturing systems. This report is supportive of a larger effort approved by the NSF/RANN Grant No. NSG-2226/RF-77-291; Definition, Development, and Implementation of a Generalized Manufacturing Simulator; GEMS.

This annotated bibliography was compiled in the early stages of the GEMS project as an effort to categorize, summarize, and compare relevant systems analysis work in the operation, analysis, and scheduling of manufacturing systems. Particular emphasis was placed upon the application of digital simulation methodologies and job shop scheduling rules to manufacturing systems. This report is being reproduced and distributed in the hope that it might aid any engineer or manager interested in the application of systems analysis/operations research methodologies to manufacturing systems.

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Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

TABLE OF CONTENTS

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Klumpar, I. V., "Process Feasibility by Simplified Simulation," Chemtech, Vol. 3, No. 2, February, 1973, pp. 88-94.

A system of computer programs for preliminary process design called Project Valuation and Estimation System (PROVES) is described. This program is applicable to most project analyses and requires no programming of specific subroutines. Part of the program package can be used separately for simplified process simulations.

The following programs are incorporated in PROVES:

MODEL (Material and Operations Design Elaborator) calculates material balances based on a simulation of unit operations.

SCOPE (Sizing and Costing of Process Equipment) determines equipment specifications and utility requirements.

INVEST (Investment Estimator) determines the complexity of the process and calculates investment cost items.

EFFECT (Economic Feasibility Using Forecasting, Estimating and Cash Flow Techniques) approximates total investment cost, determines labor requirements, detailed manufacturing costs, etc.

Petter, R. B. and R. E. Mills, "Hopsim - A Simulation Modeling Language for Health Care Systems," Vol. 24, No. 3, March 1975, pp. 73-78.

This paper deals with Conversational Modeling Language (CML) developed to simulate the utilization of a facility for delivering health care to some defined population. This language provides (1) a simulation capability, (2) a metalanguage for defining special syntax, and (3) interpretive execution.

Using the metalanguage capability of CML, a special set of syntax, HOPSIM, has been added to CML to meet the analytical requirements of many facilities utilization problems which arise in planning health care delivery systems.

Pritsker, A. B., "GERT Networks with Queueing Capabilities," paper presented at ORSA/TIMS meeting, November 10, 1972. Atlantic City, New Jersey.

The versatility of GERT in modeling complex systems led to its use in the modeling of networks of queues. The fundamental concept involved in networks of queues is the coupling of many service operations and their associated queues. In network form, a service operation is represented by a branch and would be preceded by a node representing a queueing area. Nodes of this type are defined as Q-nodes. In modeling complex networks of queues, it was found necessary to develop a concept which provided a transition between regular network nodes and Q-nodes, between Q-nodes and service activities, and between service activities and Q-nodes of successor activities. The mechanism for providing this transition has been designated as a selector-node (S-node). In this paper, a description of the Q-nodes, service activities and S-nodes will be presented along with a description of their use in GERT networks.

Pritsker, A. A. B., and J. Hebert, "Resource-GERT and the GERTS IIIR Simulation Program," paper presented at ORSA fall conference No. 2, 1972.

A capability for specifying resource requirements for activities of GERT networks has been established. Procedures for allocating available resources to meet the resource requirements of the activities have been integrated into the basic GERT framework. The product of this integration is an extended version of GERT conceptually referred to as Resource-GERT. A computer program to analyze and evaluate problems cast in the Resource-GERT framework has been developed. The resulting computer program, labeled GERTS IIIR, is a simulation package which allows the study of phenomena related to the allocation of limited resources in systems modeled as GERT networks.

Whitehouse, G. E., "Why is GERTS an Attractive Choice for Simulating Systems?" Simulation, Vol. 23, No.5, November 1974, pp. 143-48.

This article attempts to give the analyst some guidelines for making the choice between GERTS and general purpose simulation techniques. GERTS allows the analyst to simulate without performing any programming. GERTS also represents a system in a network model which aids communications with non simulators. The approximation of complicated systems using GERTS is also considered.

Aigner, Dennis J., "A Note on Verification of Computer Simulation Models," Management Science, Vol. 18, No. 11, July, 1972, pp. 615-19.

This paper establishes an argument that questions the validity of one "test" of goodness-of-fit for the simulated time path of a single endogenous variable in a simultaneous, perhaps dynamic, econometric model. This test was suggested by Cyert and Cohen, and consists of two parts, within the context of a regression of the actual series on the generated series: a test that the intercept of this regression differs significantly from zero and a test that the slope differs significantly from one.

Presumably, the intuition underlying the test is that if the simulation model is a good one, this regression should be a 45° line through the origin. The paper's primary purpose is to demonstrate that this intuition is wrong in general for the case of "stochastic simulation."

Berman, M. B., "Notes on Validating/Verifying Computer Simulation Models," Rand Papers, August 1972, P-4891.

These notes are essentially a survey of some of the existing literature on validation and verification of computer simulation models. They summarize ideas and thoughts that illuminate approaches to gaining confidence in the insights provided by computer simulation models. (Presented to members of the SHARE System Simulation Project at the SHARE XXXIX Conference in Toronto, Canada, August 9, 1972.)

Brenner, M. E., "Selective Sampling - a Technique for Reducing Sample Size in Simulation of Decision-Making Problems," The Journal of Industrial Engineering, Vol. 14, No. 6, November-December, 1963, pp. 291-96.

A tool is provided for those faced with real simulation problems involving decision making which makes the use of simulation more attractive. A sampling method is described, selective sampling, which can be used either to reduce the simulation effort for a given level of accuracy or increase the accuracy of a decision for a given amount of simulation effort. A comparison is made with other sampling methods. (author's abstract)

A Fortran subroutine for selective sampling is provided. The method is not compared to the method of antithetic variates, which was apparently developed after the publication of this article.

Brenner, M. E., "A Cost Model for Determining the Sample Size in the Simulation of Inventory Systems," The Journal of Industrial Engineering, Vol. 17, No. 3, March, 1966, pp. 141-44.

The primary focus of this article is obtaining an optimum balance between simulation cost and simulation accuracy by using an economic criterion for determining the sample size. In order to simplify the development of the cost model, a general inventory model is assumed and its associated terms defined. Also, the conditions are explained for which sample size can be determined using this cost model. A series of questions regarding the model are raised and some are answered. (author's abstract)

Carter, G. M., and E. Ignall, "Virtual Measures for Computer Simulation Experiments," Rand Papers, April 1972, P-4817.

Discussion of a technique to reduce the long simulations that are otherwise necessary before rare, interesting events occur and can be studied. The technique is based on "virtual" measures, characterized as qualities that depend on but do not alter the system image at different points in simulated time. Using a virtual measure in estimating a system characteristic may yield an estimator that has a variance an order of magnitude smaller than would result from direct measurements from the same simulation run. It often takes only nominal extra effort to calculate the virtual measure and its associated estimator, so the total computer time needed to achieve statistical reliability may be greatly reduced. The technique has been found useful in studying how to deploy NYC firefighting units so as to minimize loss of life in fires.

Dalton, O,, "Monte Carlo and Stopping Rules for some Combinatorial Problems," paper presented at ORSA/TIMS meeting, November 19, 1975. Las Vegas, Nevada.

One-machine, N-job combinatorial problems can be categorized as scheduling problems; but even for moderate requirements, no algorithm exists which can find an optimum in a livable span of time. A highly satisfactory solution was found for scheduling of a missile range (used to typify many such problems) by viewing N! possible schedules as points in a sample space, then sampling by Monte Carlo and, using Stopping Rules, estimate optimality and probability that another schedule is superior. Deviation of an optimality measure (including subjective criteria) and the results of the typical study are presented.

De Groot, M. H., "Stopping in Monte Carlo," paper presented at ORSA/TIMS meeting, November 19, 1975. Las Vegas, Nevada.

One standard technique for reducing the number of runs that are needed in a Monte Carlo experiment is the use of multistage or sequential sampling. But, in every sequential Monte Carlo experiment, a decision to stop the experiment must be made. This decision is typically made when the experimenter feels that his numerical estimates are sufficiently accurate. In this paper, various stopping rules are considered based on different definitions of information, which in turn depend on the purposes to which the information is to be put. It is shown that the distinction between a decision problem and a scientific problem is illusory.

Duket, S. D., and A. B. Pritsker, "Spectral Methods for Simulation Output," paper presented at ORSA meeting, April 30, 1975. Chicago, Illinois.

This paper concerns the development and analysis of spectral methods designed to produce confidence statements about simulated sample means. Spectral methods use lag windows to estimate the variance of the sample mean based on one simulated time series. Among those windows analyzed in the research to be presented are Bartlett, Parzen, Tukey, Rectangular, and one specifically developed for variance estimation. The evaluation is based on direct comparison to the theoretical variance as computed for the single channel queue with exponential interarrival times and exponential service times. The results indicate that spectral procedures are not reliable for making statistical statements regarding general simulation output.

Dunn, F. A., "Some Experimental Results Using Variance Reduction Techniques in Simulation," paper presented at ORSA meeting, May 5, 1971. Dallas, Texas.

Computer simulations with large models frequently require large amounts of computer time and are quite costly to run. Various techniques have been proposed in the literature for reducing variance and/or length of run. Several of these techniques were tested, together with a method developed by the author, on three different models. The results of these experiments, a discussion of the author's method, and some discussion of the objectives of the experimenter are included in this paper.

Easterfield, T. E., "A Short Cut in a Class of Simulation Problems," Operational Research Quarterly, Vol. 12, No. 4, December 1961, pp. 221-25.

This paper presents a short cut for simulation of a queueing situation in which customers arrive in large batches, more particularly for the case where there are several servers and it is material that these will not come to the end of their work simultaneously. (author's abstract)

If the number of jobs per delivery is at all large, the drawing of the job lengths and the simulation of the way they are worked off can become very time consuming. The essential step is the short cut depends on the fact that it is possible to draw values for the time taken by server to complete his job from a distribution called the Derived Distribution, which the author shows in the appendix to be of the form

$$1/T \int_t^\infty f(l)\, dl$$

where f (t) is the distribution of job lengths and T is its mean.

Fishman, G. S., "Problems in the Statistical Analysis of Simulation Experiments: The Comparison of Means and the Length of Sample Records," Rand Memorandum, February 1966, RM-4880-PR.

A continuation of research into statistical analysis of simulation experiments containing autocorrelated time series. The Memorandum shows how to estimate the lengths of sample records needed to use certain large sample results in measuring stability, describes analogies between autocorrelated data and independent observations, and suggests a way to test the difference of the mean of two experiments. It also shows how the variance of the sample mean relates to the spectrum of the generating process, and describes estimation of the quantities of interest. The results expand the possibilities of statistical spectral analysis as applied to simulation experiments.

Fishman, G. S., "Digital Computer Simulation: Estimating Sample Size," Rand Memoranda, August 1969, RM-5866-PR.

An algorithm for automatically estimating and collecting the sample size required for statistical precision in a computer simulation experiment while the simulation is running. The algorithm, which would be incorporated directly into the computer routines, would relieve an investigator of the burden of first estimating the variance of the sample mean from a data sample obtained from a trial run, then estimating the sample size necessary for the specified confidence interval, and finally collecting that many more observations in a successive simulation run. The underlying probability model is autoregressive: it would depend on an autoregressive representation of the sequence that considers each observation as a linear combination of past observations plus an uncorrelated random residual. This approach need not require more than 4 or 5 autocovariance computations to estimate the variance of the sample mean. A flowchart is included to aid in building the technique into simulation programs.

Fishman, G. S., "Estimating Sample Size in Computing Simulation Experiments," Management Science, Vol. 18, No. 1, September, 1971, pp. 21-38.

An estimate of the variance of sample mean, taking the correlation between observations into account, is useful for determining the size of a simulation experiment. The suggested method assumes that the process of interest is covariance stationary with an autoregressive representation. Criteria for the size of the experiment are discussed and illustrative examples are given.

Geisler, M. A., "The Sizes of Simulation Samples Required to Compute Certain Inventory Characteristics with Stated Precision and Confidence," Management Science, Vol. 10, No. 2, January, 1964, pp. 261-68.

The calculations presented include the number of time periods to be sampled to produce estimates of mean shortages and averages per time period within approximately 100 percent of true value with 95 percent confidence. A range of inventory policies was used for each of several lead times.

The sample sizes required to estimate shortages per period and averages per period tend not to be excessive; that is, sample sizes of less than 100 are usually required to obtain the level of precision specified above.
(author's abstract)

Gentle, J. E., "Variance Reduction and Robust Procedures in Monte Carlo Analysis," paper presented at ORSA/TIMS meeting, November 19, 1975. Las Vegas, Nevada.

In the usual statistical analyses, problems arise due to departures of the sampled population from the assumptions of the model and/or due to errors in the data. In Monte Carlo analysis, additional problems arise due to failures of the simulation process. It is, therefore, desirable to develop procedures which are robust to discrepancies between the distributions of interest and the distributions of the generated variates. Robust inferential techniques in Monte Carlo studies are considered and illustrated using various random number generators. Several methods of variance reduction in Monte Carlo analysis are discussed and compared. Applications are considered in the estimation of moments and CDFs of certain statistics useful in regression analysis.

Gunther, F. L., and R. W. Wolff, "The Almost Regenerative Method for Stochastic System Simulations," ORSA/TIMS meeting, April 2, 1976. Philadelphia, Pennsylvania.

The regenerative method for simulation of stochastic systems allows data collection each time the stochastic process enters a specific single state, r, called the regeneration state. Estimates of estimator variance are then easily computed since the generated observations have the desirable property of being independent and identically distributed. Relative to a fixed run length, however, the mean time between entries into r may be excessively long for complicated stochastic systems (e.g., a network of queues), thus providing few observations and poor variance estimates. The almost regenerative method is an extension of the regenerative method designed to alleviate this problem for complicated stochastic systems. The new method allows data collection each time the stochastic process enters a set of states. Simulations of simple queueing networks show that the almost regenerative method can provide an order of magnitude reduction, relative to the regenerative method, of the mean-square-error of the total delay in queue estimator, and this relative improvement increases with system complexity. Additionally, the new method provides more accurate variance estimates. Similar results are true when the almost regenerative method is compared to the frequently used fixed time increment method for event-oriented simulations.

Hauser, N., N. N. Barish, and S. Ehrenfeld, "Design Problems in a Process Control Simulation," The Journal of Industrial Engineering, Vol. 17, No. 2, February, 1966, pp. 79-86.

This article is concerned with the study of methods and problems relating to the simulation of the stochastic output of a process control simulation. Aspects which are treated include questions of efficiency and stopping rules for deciding on the length of simulation run to achieve a desired confidence level for estimates. Some of the problems of computer computation are considered, and methods for solving them are suggested. (authors' abstract)

Kiviat, P. J., "The Validation of Computer System Simulation Models: A Practitioner's Approach," paper presented at ORSA meeting, November 14, 1973. San Diego, California.

The Federal ADP Simulation Center uses a variety of simulation tools in performing ADP systems simulation and computer performance evaluation. Among the tools are SCERT, CASE, ECSS, SIMSCIPT II, and GPSS. Simulation models are used to evaluate proposed configurations, predict system performance, estimate the size of a system to support a stated requirement and assist in design of new hardware and software. Each use has different validation requirements. The paper discusses the range of validation requirements and how the Center acts to meet them.

Kleigner, J. P. C., "Antithetic Variates, Common Random Numbers, and Optimal Computer Time Allocation in Simulation," Management Science, Vol. 21, No. 10, June, 1975, pp. 1176-85.

The purpose of the paper is to derive a variance reduction procedure for simulations of queueing systems giving optimum computer time allocations. Two common techniques are antithetic variates and common random numbers (correlated sampling). There are three alternatives: antithetics only, common random numbers only, and the two combined. No alternative is always best. The author describes how to select the most appropriate alternative for a particular problem.

Lavenberg, S. S. and D. R. Slutz, "Introduction to Regenerative Simulation," IBM Journal of Research and Development, Vol. 19, No. 5, September, 1975, pp.458-62.

A method is reviewed for estimating confidence intervals within regenerative simulation and the associated sample sizes. The method is applied to M/G/1 queues when the arrival rate is less than the service rate. In the M/G/1 queue, one may identify the regeneration points through simulation as those points wherein the queue is empty. One may then derive estimates of waiting time and its variance by simulating a series of regeneration points and using generated data on total service time and customer service time.

Estimates of the length of simulation runs are given.

Law, A. M., "A Comparison of Two Techniques for Determining the Accuracy of Simulation Output," paper presented at ORSA meeting, April 30, 1975. Chicago, Illinois.

Suppose that enough computer time is available to make n observations of a simulated system. In order to estimate a population parameter of the system, a person may make k independent runs each of length m observations (n is k times m). This is known as the method of replication. Alternatively, a person may make one long run which he then divides into k batches each of length m. This is known as the method of batch means. In this paper we consider how to optimally choose k and m for the two methods. We then compare the two methods themselves.

Morgan, A., "Stag Monotone Experimental Design Algorithm (SMEDAL)," Management Science, Vol. 20, No. 2, October, 1973, pp. 214-20.

In using a computer simulation to gain insight into a planning problem, repeated runs over a range of input variables can be used to develop a picture of the general response of the system being studied. SMEDAL was developed to help organize such studies and, in particular, to help eliminate redundant computer runs. If the planning problem can be interpreted as a question of feasibility (i.e., will we win or lose?) and if the system under study exhibits a "monotone" property, the SMEDAL can be applied. Furthermore, SMEDAL is not limited to computer applications but can be used to save effort in any such study.

Sassen, W. E., D. S. Burdick, D. A. Graham, and T. N. Naylor, "The Application of Sequential Sampling to Simulation: An Example Inventory Model," Communications of the ACM, Vol. 13, No. 5, May, 1970, pp. 287-96.

Sequential sampling is used to save computer time in drawing conclusions of a predetermined accuracy about total cost from multi-item stock simulations with replicated data. Thus the sample size N is a variable dependent on the outcome of the first N-1 simulations. A decision about the significance of total cost is made after each simulation - either to accept the hypothesis, to reject it, or to go on simulating.

Cost savings made by sequential sampling, compared with fixed size sampling, are shown for four different sequential procedures applied to the results of computer simulations of a stock system.

Schaefer, B. M., "Model Validation Using Simulation and Sequential Decision Analysis," paper presented at ORSA meeting, April 30, 1975. Chicago, Illinois.

A method of evaluating alternative mathematical models of an observed process is presented. The method involves the simulation of the alternative models, and compares the results of these simulations with the observed process to obtain order statistics. These order statistics are then used in a sequential decision algorithm that chooses the most valid model once enough data has been obtained.

Schaefer, B. M., "Model Validation Using Simulation and Sequential Decision Theory," paper presented at ORSA/TIMS meeting, November 18, 1975. Las Vegas, Nevada.

In a recent paper by the author a method of validating simulation models using sequential decision theory was presented. This paper extends this method in two directions. It is shown that the method is applicable for systems in which the state vector is of dimentionality larger than one, as well as systems in which the state is observable only in the presence of noise. This noise may be of a multiplication or additive nature; the only requirement is that, if the observation vector is given by $y(t) = g(x(t), v(t)$ where $x(t)$ is a state vector and $v(t)$ is the observation noise, then there must exist an inverse function such that $x(t) = h(y(t)$ $v(t))$.

Siff, F. H., "Variance Reduction in Simulation Studies-Conditional Monte Carlo," paper presented at ORSA/TIMS meeting, November 17, 1975. Las Vegas, Nevada.

A methodology for efficient analysis of simulation generated time series is presented. Generally referred to as conditional Monte Carlo, analytic solutions of portions of a model are used to condition the relevant sample space. In this application, the problem of estimating the mean value function of a stationary time series is thereby transformed into a process of taking linear combinations of independent estimates of the expectations of simple random variables. Numerical results are discussed for an economic model of the firm and applied to capital investment selection.

INVENTORY MODELS

Barten, K., "A Queueing Simulator for Determining Optimum Inventory Levels in a Sequential Processor," The Journal of Industrial Engineering, Vol. 13, No. 4, July-August 1962, pp. 245-52.

This paper deals with the problem of how much storage space to provide between any two sequential tasks in a series of operations. Storage capacity optimization is estimated through the use of a simulation model. The model, which is well described in the article, is a simple network model with stochastic operation times, limited queues, and blocking. The reduction in delay time achievable through increasing storage or "buffer" capacity was found to be, in general,

$$y = k\, x^{-0.65}$$

where x is the storage capacity and k is a constant which varies with the number of operations in the sequence. From this relationship and cost considerations, optimal buffer capacity can be determined.

Berman, E. B., "Monte Carlo Determination of Stock Redistribution," Operations Research, Vol. 10, No. 4, July-August, 1962, pp. 500-506.

A model was designed for the purpose of studying stock distribution policies in an inventory system consisting of a number of demand points distributed through space. The model is limited to items that are not centrally repaired and are procured only once during the life of the item. The expected system costs are determined by Monte Carlo methods. (from author's abstract)

The model seems to be too restricted to be of interest to a study of general manufacturing simulation.

Clark, A. J., "The Use of Simulation to Evaluate a Multi-Echelon Dynamic Inventory Model," Naval Research Logistics Quarterly, Vol. 7, No. 4, 1960, pp. 429-45.

Simulation is normally used to investigate a problem that is too complex for analytical solution. However, it is possible to have a solution algorithm that is itself so complex that simulation may profitably be used to study its behavior. A case in hand is a recently developed multiechelon inventory decision model which uses dynamic programming techniques. The use of simulation to evaluate this decision model is illustrated by a case study of a fictitious but realistic item. In particular, its use for comparative analysis of different maintenance policies is explained.

Additional uses of simulation in this context are mentioned. For example, the insertion into the simulation of complexities not included in the decision model provides a qualitative evaluation of the use of the decision model in an actual logistics system. Also, the ability of the decision model to cope with increasing information may be analyzed.

Dickson, G. W., and P. Mailandt, "Some Pitfalls of Solving Inventory Problems by Simulation," Production and Inventory Management, Vol. 13, No. 2, 2nd quarter 1972, pp. 74-86.

The author's main point seems to be that in a short computer run one may obtain an answer which is not precise, and in a very long run, one may consume one's saving in computer time. As an example, he gave a problem characterized by probabilistic demand and order lead times plus the consideration of the cost of stockouts. The author used the standard square root lot size formed to obtain a reorder quantity (ROQ) of 200 and a reorder point (ROP) of 180. Simulating one year of operation with various (ROQ, ROP) combinations, he found a minimum point at (300, 225). Simulating in fine increments around this point, he found results somewhat contradictory to his first run. So he simulated for 10 years, then 300 years before finding a true minimum at (200, 250).

The author points out that for this item the 300 year simulation found that the analytical solution would cost "only" $428 per year, whereas the optimal solution cost $278 per year, a savings of $150 per year. Since the 300 year simulation consumed 5.5 minutes of CDC 6600 processor time, he argues that the benefits of the simulation approach are outweighed by the cost.

It seems to me that the author disproves his own argument. From his figures, a one year simulation would consume about 1.1 second of processor time. The one year solution first found (300, 225) was shown by the 300 year simulation to have an average cost of $286 per year. What the author really demonstrated is that he saved $142 a year with his first cut using simulation, and only managed to beat that answer by $8 per year when he finally found the true minimum. One could hardly find a better argument for producing one year of simulation runs around the analytical solution.

Dzielinski, B. P. and A. S. Manne, "Simulation of a Hypothetical Multi-Time Production and Inventory System," Journal of Industrial Engineering, Vol. 12, No. 6, November-December, 1961, pp. 417-21.

This report is of an early study of the interaction of inventory decisions and production. The model used is extremely restrictive - a single bottleneck facility, identical customer demand rates, identical manufacturing times for all items, etc. There is a flow chart of the system presented but no discussion of simulation language or other techniques. The article seems to have little to interest the modern student.

Dzielinski, B. P., C. T. Baker and A. S. Manne, "Simulation Tests of Lot Size Programming," Management Science, Vol. 9, No. 2, January, 1963, pp. 229-58.

This paper presents the results of some digital computer simulation tests of a procedure for the economic planning of lot sizes, work force, and inventories. A dynamic, deterministic, linear programming model was used to obtain approximate solutions to the actual problem which is both dynamic and stochastic. The tests were made with data takes from an actual factory. An alternate procedure, based upon single-item inventory control, was also tested; its results were compared with those obtained from the linear programming model. On the basis of these tests, this linear programming method appears to offer a promising method for the practical economic planning of production activities. (author's abstract)

Eilon, S. and J. Elmaled, "An Evaluation of Alternative Inventory Policies," International Journal of Production Research, Vol. 7, No. 1, 1968, pp. 3-14.

The article compares the performance of five alternate inventory control policies and shows how a simulation model could be used to monitor the effect of dynamic demands.

Generally, an inventory control policy is determined using past data without any provision to re-evaluate any of the parameters derived from the policy. In dynamic situations where the demand could vary considerably due to a number of factors, it is important to re-evaluate and monitor the policy. Five policies are chosen and a simulation is carried out; the results are compared.

Fairhurst, J. H., and D. Livingstone, "A Simulation Model for Production Inventory Decisions," O. R. Quarterly, Vol. 24, No. 2, pp. 299-304, (2 refs.).

The paper describes initial simulation work on various factors associated with production and inventory decisions. The machine shop models which were used comprised of one machine only on which a small product range is manufactured. The effect of variations in output mix and demand levels on the rate of return on investment is examined. The necessary adjustments in stocking policy for an economic level of capability utilization are indicated, and a "capacity profile" is produced which reveals the efficient operating frontier for the different cases. The direction of further experiments is indicated.

Lawson, W. H., "Elements of Inventory Simulation," Automation, Vol. 11, No. 1, Jan. 1964, pp. 65-67.

The author, then assistant to the controller of Toledo Scale Corp., reported that at that plant, "it was demonstrated that if certain revised policies had been in effect during a given six-month period, inventory investment in the parts sampled would have been reduced 43 percent, with no significant change in customer service." The author briefly and non-technically discusses some model considerations when using computer simulation to determine reorder points and economic order quantities.

Meyer, U. and M. P. Groover, "Multiechelon Inventory Systems using Continuous Systems Analysis and Simulation," AIIE Transactions, Vol. 4, No. 4, December, 1972, pp. 318-27.

The purpose of this article is to investigate the economics of theoretical multiechelon inventory systems by continuous system simulation, and to compare continuous system simulation with an analytical approach and linear assumptions.

The simulation approach permits the investigator to formulate a nonlinear model but introduces the need for multiparameter search to seek (not necessarily find) minimum cost.

Muyen, A. R. W., "Optimum Lot-Size Policy if Tools Break Down Frequently," Operational Research Quarterly, Vol. 12, No. 1, May, 1961, pp. 41-53

A well-known formula gives the optimum length of a production series by balancing change-over costs against inventory costs. This formula can no longer be considered optimum in the case of a high breakdown rate of the tools. We can often reduce our costs in such situations by ending the production series when a breakdown occurs. This introduces a variability in the lot-sizes, which in turn causes higher stock levels.

A production policy was developed, based on two limits Q_1 and Q_2. Production is stopped either at the first breakdown after Q_1 units have been produced, or at Q_2. Optimum values of Q_1 and Q_2 have been developed and can be read off from a set of graphs.

One assumption of this theory is that tools are always available, which theoretically requires an infinite stock of these tools.

A Monte Carlo programme was set up to study the situation, in which the number of tools was limited. The number of tools, and the reorder-level for the products, required for a desired probability of stock out, can be derived by the programme.

The theoretical values of Q_1 and Q_2 could be considered optimum for practical purposes in the case under consideration. (author's abstract)

Naddor, E., "Markov Chains and Simulations in an Inventory System," The Journal of Industrial Engineering, Vol. 14, No. 2, March-April, 1963, pp. 91-98.

An inventory system is described in which the forecast of future demand is part of the inventory model. A Markov chain approach and a simulation approach are compared in finding the effect of the decision variables on expected amounts of inventory in the system, the number of shortages, and the frequency of replenishments. Although the Markov chain approach is quite feasible, the simulation approach is simpler and gives results very close to those obtained using the Markov chain. (author's abstract)

Packer, A. H., "Simulation and Adaptive Forecasting as Applied to Inventory Control," Operations Research, Vol. 15, No. 4, July-August, 1967, pp. 660-679.

This paper describes a case study of selected inventory accounts maintained by a large manufacturer of rocket engines. It was hypothesized that a significant improvement in average inventory levels, number of purchase orders, and number of stockouts could be obtained by augmenting existing methods of inventory management with certain OR based techniques. These techniques included exponential smoothing of demand forecasts and statistical determination of optimum safety stock levels. Computerized simulation was used to determine: 1) the most effective parameter (α) values for use in the exponential smoothing formulas; 2) an estimate of the potential dollar savings obtainable if the proposed methods were implemented; and 3) a means by which these methods could be implemented.

Prokop, J. S. and F. P. Brooks, Jr., "Decision Making with Computer Graphics in an Inventory Control Environment," Proc. AFIPS, Fall, 1970, Joint Comp. Conf., pp. 599-607.

This paper describes a well conceived experiment in which 18 people participated. Near the end of 20 hours of instruction in advanced inventory control techniques, each participant was given statistics resulting from two different simulation runs. In one run, all information appeared as hard-copy tabular listings. For the other runs, subsets of the listing could be displayed via the Programmed Function Keyboard of an IBM 2250.

The results support the conclusion that better decisions can be made earlier and faster using displays instead of printout.

Roberts, P. C. and M. J. Branison, "The Commonality Problem in Stock Control for Complex Assemblies," O. R. Quarterly, Vol. 20, April, pp. 71-85.

A method is described for maintaining overall inventories close to the minimum level, in the situation of keeping stocks of parts to be issued for assemblies. Simulation results show that the minimum total inventory level is reached when approximately 80% of the assemblies can be commenced at the scheduled time. Furthermore, by additional simulations it is shown that this performance figure can be obtained by a 30% increase in inventory if inferior strategies are used. The power of the method is directly related to the wide range of item values and item commodities that are present.

Schaack, J. P. and E. A. Silver, "A Procedure, Involving Simulation, for Selecting the Control Variables of an (S,c,s) Joint Ordering Strategy," Infor., Vol. 10, No. 2, June 1972, pp. 154-170.

This paper considers an inventory situation where the control procedure is dependent in nature, i.e., an item that would not be ordered at a particular point in time if it was being controlled independently, is allowed to be included in a replenishment trigerred at that moment by the necessity of ordering another item. In particular, we develop a procedure for selecting the control variables (order-up-to levels, can order points, and must-order points) of an (S,c,s) system. The procedure, iterative in nature, is a combination of mathematical optimization and simulation. The cost savings over a usual independent inventory system are demonstrated. (author's abstract)

Sterling, E. B., "A New Commodity Management Tool: Uniform Inventory Simulation Modeling," Defense Management Journal, Vol. 11, No. 4, October, 1975, pp. 65-68

An explanation is given of the inventory operations of Defense Supply Agency, emphasizing the complexity and diversity of this supply support agency of Department of Defense. The paper concentrates on explaining a set of simulation programs designed to test developments and adjustments to the actual system: Standard Automated Material Management System.

Ackerman, S. S., "Even-Flow, a Scheduling Method for Reducing Lateness in Job Shops," Management Technology, Vol. 3, No. 1, May, 1963, pp. 20-32.

The Even-Flow method is described. Method involves two assumptions: (1) the operation time, i.e., the actual time spent on a machine, is small compared to the total time the job spends in the shop, and, (2) the movement time between machine centers plus waiting time for a machine is approximately the same for all operations. Even-flow operates by first producing an overall schedule of all jobs, such that expected arrival time at each station is known for all jobs. Dispatching is handled by a two queue system at each work station; with jobs arriving late at any work station going to the priority queue. Best results obtained when selection from each queue was on the basis of S.I.

A five machine job shop is simulated comparing the even flow rule to random selection, first in first out, and smallest operation time. Some improvement was noted. The author warns that the results represent a preliminary study under controlled conditions.

Bulkin, M. H., J. L. Colley, and H. W. Steinhoff, Jr., "Load Forecasting, Priority Sequencing, and Simulation in a Job-Shop Control System," Management Science, Vol. 13, No. 2, Oct. 1966, pp. B29-51.

This paper reports the development, installation, and evaluation of a simulation which sequences shop operations for the next shift at the El Segundo Division of Hughes Aircraft Corp. Simulation outputs give each foreman the priority of jobs currently in his section and those jobs which might be coming through his area during the next work period. The foreman can determine in advance what tools, raw materials, etc., are needed and obtain them, thus tending to eliminate queue time for hot jobs.

In three months of operation, the simulation has been more successful than initially expected. Coordination and expediting efforts have been reduced, in process inventory has been reduced along with worker idle time, and schedule performance has improved. An additional important result noted during this time is an enlargement of the foreman's job. He has less need for coordinators and expeditors since he has the information needed to make rational decisions on sequencing the work.

Hughes-El Segundo shop is characterized by a diverse product mix flowing through functionally diverse work centers. There are 2,000-3,000 orders in process at any one time with an average of seven functional operations per order. The average operation requires $2\frac{1}{2}$ hours processing time. The shop consists of 1,000 machines grouped into 120 work stations. There are 400 direct workers.

To assist fabrication management in determining the manpower capacity and work load required to achieve production objectives, a computer generated Shop Load Forecast is prepared weekly. The Forecast displays the remaining standard hours of work load associated with all orders in the Fabrication Open Order File.

To aid fabrication operating personnel in regulating the flow of orders through the functional machine groups, two types of reports are prepared each day. These are status reports and simulation output. Status information is provided through Location and Coordination Reports which are complete listings of all open orders. The Order Schedule and Hot Order Visibility Reports are the output of a daily simulation scheduler. These reports are used by shop foremen and coordination personnel in the daily sequencing of jobs at the machine groups in the shop. The prescribed priority rule used in the scheduler is the Minimum Slack-Time Per Operation Rule.

The Order Schedule Report shows, for each machine group in the shop, the orders in station at the beginning of the shift and the orders expected to arrive during the shift. The entry for each in-station order shows where the order came from, the order quantity, the work context of the operation, and the work context remaining beyond the operation in the machine group. With this visibility as to incoming orders, a foreman's job becomes one of planning the day's work rather than one of fighting it.

The Hot Order Visibility Report shows, for each department in the shop, all "hot" coded orders located in the department at the beginning of the shift. With this information, a coordinator's job becomes one of systematically monitoring the flow of orders rather than one of convincing foremen to work his job first.

Conway, R. W., "Priority Dispatching and Work-In-Process Inventory in a Job Shop," The Journal of Industrial Engineering, Vol. 16, No. 2, March-April, 1965, pp. 123-130.

The present article is a progress report on a study reported earlier by Conway, Johnson, and Maxwell (1960). Recent programs have been written in SIMSCRIPT and executed on an IBM 7090, increasing the run length by a factor of about 30 over those previously reported. The shop studied has been increased from five machines to nine. The authors found that no single rule exhibited the best performance for all of the different measures simultaneously; nevertheless, shortest processing time (SPT) dominated the set of rules tested. "It can be concluded that SPT has earned the right to be considered as the standard (rather than FCFS [first come first served]) in scheduling research against which candidate procedures must exhibit their virtues."

Conway, R. W., "Priority Dispatching and Job Lateness in a Job Shop," The Journal of Industrial Engineering, Vol. 16, No. 4, July-August, 1965, pp. 228-36.

This report is a continuation of Conway (1965, 1) and Conway, Johnson and Maxwell (1960). The present article considers the results of simulation of priority dispatching rules that are applicable to the question of job lateness. It was already known that the priority rule exhibiting minimum mean shop time must also exhibit minimum mean lateness. Previous studies by Conway had established the shortest processing time (SPT) rule as exhibiting minimum mean shop time among the alternatives considered. It had generally been believed that this virtue of SPT was offset by a large variance in late times. The present study obtained the surprising result that SPT ranked second in reduction of variance among alternatives considered.

One priority rule which outperformed SPT in some instances was the slack per operation (s/opn) rule. In determining priority under this rule, one subtracts remaining processing time from the time until due date and divides by the number of operations remaining. Use of this rule can reduce the percentage of jobs which are late.

Conway, R. W., B. M. Johnson and W. L. Maxwell, "An Experimental Investigation of Priority Dispatching," The Journal of Industrial Engineering, Vol. 11, No. 3, May-June 1960, pp. 221-30.

Simulation was used to study the relative merits of thirteen priority dispatching rules including random, first in-first out, due date, "slack" time, shortest and longest operating time, etc. The shop consisted of five machines, job movement between machines was randomly generated from a table of probabilities of job movement from machine to machine. This is an extremely early study. One of the stated objectives was "to find out if serious investigations by means of digital simulation could be pursued on a medium-scale (magnetic drum) digital computer."

Conway, R. W. and W. L. Maxwell, "Network Dispatching by the Shortest-Operation Discipline," Operations Research, Vol. 10, No. 1, Jan.-Feb. 1962, pp. 51-73.

The significance of the dispatching function in production planning and control is discussed and the applicable results in sequencing and queueing theory are reviewed. Experimental results for a network of queues representing a small job shop are presented. The investigation involved the comparison of dispatching at random with dispatching in order of increasing processing time under different conditions of shop size, flow pattern, and level of work-in-progress inventory. Also considered is the effect of imperfect a priori knowledge of processing times upon the shortest-operation discipline. Several modifications of the shortest-operation discipline were also tested: one in which the shortest-operation discipline is "truncated" and another in which it is periodically alternated with a first-come-first-served discipline. (author's abstract)

Eilon, S. and D. J. Cotterill, "A Modified SI Rule in Job Shop Sequencing," International Journal of Production Research, Vol. 7, No. 2, 1968, pp. 135-45.

The scheduling problem is concerned with determining the sequence in which the jobs should be processed on each machine. One rule which has been found to be effective is the SI rule which postulates that highest priority should be given to the one job in a queue which has the shortest imminent processing time. A simulation study showed that the SI rule could be improved if jobs which were approaching their promised delivery date were placed in a second, higher priority queue. Their position in this second queue was also decided by the SI rule.

Fabrycky, W. F., "A Simulation Study of Three Classes of Job Shop Sequencing rules," American Production and Inventory Control Society, International Conference Proceedings, October, 1970, (published 1971), pp. 247-56.

A number of papers have been published on job shop sequencing techniques, with a view to maximizing or minimizing given criteria. Most of the rules fall into three categories. A simulation study is carried out here to compare the effect of using the rules on the criteria of due date performance of completed orders. Both tight and normal due date conditions are investigated. Certain observations are made by comparing the results of the simulation runs.

Gere, W. S., Jr., "Heuristics in Job Scheduling," Management Science, Vol. 13, No. 3, November, 1966, pp. 167-90.

The problem is that of scheduling jobs with diverse routings on the productive facilities in a shop such that the respective due dates are met, or failing this, the sum of lateness times is minimized. The problem is simulative in that the operation of the shop is simulated in a Fortran program, but in addition to the straightforward use of priority rules for determining sequences of jobs on the machines, a number of heuristics or rules of thumb are incorporated. Both the static (all jobs on hand at time zero) and dynamic problems (new jobs admitted from time to time) are investigated. The efficacy of a small number of heuristics in combination with certain priority rules is demonstrated; in particular the "alternate operation" and "look ahead" routines will improve schedule significantly when used to augment a reasonable priority rule (job slack, job slack ratio, length of next operation; length of operation plus job slack ratio, first-come-first-served). The selection of the priority rule itself is a relatively unimportant matter. The authors did find that the first-come-first-served rule did not significantly improve upon random selection. All of the other rules improved significantly upon first-come-first-served. Since the heuristics resulted in improvement over any priority rule, the use of a single priority rule is recommended.

The program also appears to yield highly satisfactory solutions for the "minimum make span" problem, a problem in which the last job is to be completed as soon as possible.

Heller, J. "Some Numerical Experiments for a Flow Shop and its Decision-Theoretical Aspects," Operations Research, Vol. 8, No. 2, March-April, 1960, pp. 178-84.

The article contains the results of some over-simplification in the numerical solution to scheduling simulation experiments on an IBM 704 computer. Using an MXJ model, the author has concluded normal distribution as opposed to asymptomatically normal found in the theoretical analysis of large-scale job scheduling. He sampled different schedules in a flow shop in an effort to find a "best" schedule and also to examine the value of random sampling in solving sequencing problems. The presentation is good but presupposes the availability of reference materials for complete explanations.

Hershauer, James C. and Ronald J. Ebert, "Search and Simulation Selection of a Job Shop Scheduling Rule," Management Science, Vol. 21, No. 7, pp. 833-843.

A standardized approach to selecting simple sequencing rules for decentralized application throughout a job shop is developed and illustrated. The sequencing rule is a linear combination of decision factors, each of which is initially assigned a relative weighting. The rule is then used to determine the priority of each job in the queues and the resulting shop costs are determined by computer simulation. The coefficients of the priority function are thereafter modified by a patterned search procedure to find priority coefficients that minimize the expected cost per order for a specified cost structure. The cost structure is a combination of multiple response measures for the shop. Rather than leading to a 'single best rule' for all job shops, the approach is a 'method for finding' a sequencing rule that performs well in any specific job shop situation.

Hollier, R. H., "A Simulation Study of Sequencing in Batch Production," O. R. Quarterly, Vol. 19, No. 4, 1968, p. 389-407.

A batch production shop can be considered as a network of queues of jobs awaiting service by the available facilities, mainly machines. One of the major controllable variables in this context is the sequencing of jobs when machines become idle, and their decision area could be looked upon as the final phase of scheduling before machines are actually committed to a certain course of action.

A hypothetical batch production system was modelled and simulated to test (1) the effects of various sequencing decision rules and parameter values and (2) to assess the usefulness of a number of measures of system performance.

The program was written in Fortran. Three main type of analyses were carried out. First, an analysis of variance was performed for the different sequencing rules and for the various measures of performance used. Second, some characteristics of the distributions of individual delay and throughput time were investigated. Third, regression equations were calculated for prediction of throughput time.

Hottenstein, M. P., "A Simulation Study of Expediting in a Job Shop," Production and Inventory Management, Vol. 10, No. 2, second quarter, 1969, pp. 1-11.

Expediting job shop operations produces interactions that affect inventory, waiting time, delivery dates and performance variability. Computer-programmed simulations of job shops compare expedited order control with non-expedited or "shortest possible processing time" control.

The simulation study found that use of expediting significantly increases the average time a job spends in the shop by increasing waiting time per job.

LaRobardier, L. M., "Planning and Scheduling of DYNAMĪT," Industrial Engineering, Vol. 5, No. 12., December, 1973, pp. 38-41.

Dynamīt is a time-cost-quality network approach that utilizes both dynamic programming and branch-and-bound procedures to test the complete set of schedules that fit within capacity and also satisfy sales requirements. It selects the minimum cost schedule, provides projected inventory and setup costs and also comparative costs for alternative procedures. It also provides a specific sequence of production to be followed by operation personnel.

Maxwell, W. L., "Priority Dispatching and Assembly Operations in a Job Shop," Rand Memoranda, October 1969, RM-5370-PR.

An experimental investigation of priority dispatching in a job shop whose output feeds into an assembly shop. Procedures are investigated for meshing the jobs related to a product by either (1) having jobs progress at the same rate based on information about the number of operations remaining, or (2) having jobs completed by some due date. Two-level priority procedures are presented that group jobs by how critically their completion affects the assembly of their product, and then use a shortest-processing-time (SPT) method within these major groupings. Statistics are collected that indicate where congestion occurs and help in deriving some of the priority rules. It is found that better overall performance is achieved by combining the SPT rule with product-oriented rules. Areas for future research include both procedures (e.g., the use of SPT in the job shop) and the assembly environment.

New, C. C., "Matching Batch Sizes to Machine Shop Capabilities: An Example in Production Scheduling," Operational Research Quarterly, Vol. 23, No. 4, December, 1972, pp. 561-72.

The case studied is where a job-shop has repeat orders due for delivery at monthly intervals into the future; these orders have to be batched, and the batches scheduled through several general-purpose machines, so that all lines of all orders are completed by the due dates. Set-up and operating times are fixed.

The decision variables are how much to schedule and when (the"launch period"). The Economic Batch Quantity formula is inadequate for deciding batch quantities in this situation. The decisions concerning batch quantity and launch period interact, so they should be made simultaneously.

Heuristics were sought which take account of the current workload to decide batch quantity and launch period simultaneously. The effectiveness of the heuristic was evaluated by a simulation of a job shop having 75 machines. Lateness of orders was substantially reduced.

Raja Raman, M. K., "A Parallel Sequencing Algorithm for Minimizing Total Cost," ORSA/TIMS meeting. November 17, 1975. Las Vegas, Nevada.

The problem of sequencing jobs on parallel processors when jobs have different available times, due dates, penalty costs, and waiting costs is considered. The processors are identical and are available when the earliest job becomes available and continuously thereafter. There is a processor use cost during the period when the processor is available for processing jobs. The algorithm finds the sequence (or sequences) with minimum total cost (sum of waiting, penalty, and processor use costs). A proof of the algorithm and numerical results are given.

Randolph, P. H., "Stopping Rules for Sequencing Problems," paper presented at ORSA/TIMS meeting, November 8, 1972. Atlantic City, New Jersey.

Monte Carlo methods have been proposed for finding solutions to sequencing problems. One deficiency of these methods has been the absence of appropriate rules for stopping the sampling process. This paper examines stopping rates that not only have been effective for choosing a sequence but also provide a measure of the quality of the sequence chosen.

Rouchette, R. and R. P. Sadowski, "A Statistical Comparison of the Performance of Simple Dispatching Rules for a Particular Set of Job Shops," International Journal of Production Research, Vol. 14, No. 1, 1976, pp. 63-75.

The model developed concerns the operation of a set of needle trade manufacturers. The operation involves a certain number of distinct departments, work centers within departments and operators that can be assigned to any work center within a given department (worker flexibility). Job orders are generated according to Poisson arrival, and job routing is randomly generated from the set of fixed routings available. Service time is exponential. An experimental design consists of several simulation runs under varying shop conditions using eight different priority rules and two measures of performance. Statistical comparisons of different runs are made and conclusions regarding effectiveness of various priority rules and worker flexibility are drawn.

Story, A. E. and H. M. Wagner, "Computational Experience with Integer Programming for Job-Shop Scheduling," from Industrial Scheduling, J. F. Muth and G. L. Thompson, eds., Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963, pp. 207-19.

The authors found that for a three machine problem with eight or more items, over 1000 iterations were usually required for solution: The authors state: "One conclusion is evident from the tests: we have not yet found an integer programming method that can be relied upon to solve most machine sequencing problems rapidly."

Thompson, G. L., "Recent Developments in the Job-Shop Scheduling Problem," Naval Research Logistics Quarterly, Vol. 7, No. 4, Dec. 1960, pp. 585-89.

The job-shop scheduling problem is a large-scale combinatorial problem of great practical significance. First, a discussion of the size of the combinatorial problem involved will be given. Then, the various methods of attacks for solving this problem will be discussed and criticized by the use of examples. These methods include principally the integral linear programming, the heuristic, the loading rule, the simulation, and the Monte Carlo methods. The latter method, in the form devised by Giffler and Thompson, will be described in detail, and some computational results will be presented. (author's abstract)

Giffler and Thompson have devised an algorithm for the complete enumeration of all active feasible schedules. They define an active feasible schedule to be one with the following properties: (a) no machine is idle for a length of time sufficient to completely process a simultaneously idle commodity, and (b) whenever an assignment of a commodity to a machine has been made, its processing is started at the earliest time that both the machine and the commodity are free. At the time this article was printed, a six commodity, five machine problem was the largest which had then been solved, however, work was under way on a 200 commodity, 10 machine problem.

Trinity, R. C., "On the Job-Shop Scheduling Problem," from Industrial Scheduling, J. F. Muth and G. L. Thompson, eds., Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963, pp. 59-75.

This paper is a mathematical treatment of certain aspects of the job-shop scheduling problem. Markov chains are used to determine the distribution of waiting times for one specific model. However, in order to do this, first come first served queue discipline is assumed. Since FCFS has been shown to be a poor decision rule, the fact that one can determine its distribution of waiting times is of little value.

The paper also discusses the determination of an "optimal sequencing procedure." Unfortunately, the model used considered only a fixed charge for late jobs, rather than a charge per time period. Also, even this simplified model must be solved recursively. It would seem that computational expense could easily exceed any savings generated by use of the model.

Vergin, R. C., "Production Scheduling under Seasonal Demand," The Journal of Industrial Engineering, Vol. 17, No. 5, May, 1966, pp. 260-66.

This article attempts to look at the broad question of the application of the results of scientific inquiry to the problem of scheduling aggregate production, employment, and inventory levels under conditions of seasonal demand. Scheduling data and a description of methods currently being used to deal with this problem were obtained by research conducted in eight Minneapolis area manufacturing firms having highly seasonal demand patterns. Algorithms used to solve the scheduling problem were: linear programming-transportation model, linear programming-simplex method, quadratic programming-linear decision rule model, and simulation by an easily modified Fortran program. After the simulation model was tailored to a particular firm, scheduling was made on a trial and error procedure using certain guide rules. Only three firms were used in the simulation portion. Total firm costs were reduced by 2.2, 1.5, and 1.0 percent over schedules being used by management. The simulator was also used to develop a payoff schedule for various demand patterns and to determine the effects of errors in demand forecasting and cost estimation.

AGGREGATE PRODUCTION PLANNING MODELS

Lee, B. and Khamawala, B. M., "Simulation Testing of Aggregate Production Planning Models in an Implementation Methodology," Management Science, Vol. 74, pp. 903-911.

The planning of production, inventories, and work force at an aggregate level to respond to fluctuating demands on a production system has received substantial theoretical treatment in the literature for several years. However, widespread implementation of the available analytical techniques has not occurred. The objectives of this research are to explore this implementation problem: (1) by developing a simulation model of an operating firm, (2) by using this simulation to compare the performance of aggregate production planning models, and (3) by formulating a generalized methodology for implementing quantitative planning models into the decision procedures of operating firms.

Four aggregate planning models are compared: the Linear Decision Rule, Management Coefficients Model, Parametric Production Planning Model, and the Search Decision Rule. This research was conducted with the cooperation of a firm in the capital goods industry having annual sales of approximately $11 million. A simulation model (CORSIM) of the firm was developed which follows closely the accounting system and the material flow through the organization: It simulates the operation of the firm from an aggregate level and does not incorporate the details of individual products. Validity of the model was developed by using both the experience and intuition of management and the analytical techniques of management science.

Perhaps the most important question tested concerns whether the firm could have made greater profits if management had used one of the four aggregate planning methods which this study evaluated. The results are published in the

table below. Other published studies have received such results. However, in only particular situations the magnitude of increased profits cannot be determined a priori.

Table of Corporate Profit Performance

	Imperfect Forecast	Perfect Forecast
Company Decisions	$4,420,000	$
Linear Decision Rule	4,821,000	5,078,000
Management Coefficients Model	4,607,000	5,000,000
Parametric Production Planning	4,900,000	4,989,000
Search Decision Rule	5,021,000	5,140,000

This research provides additional evidence in a realistic test situation that firms can achieve better performance by the implementation of aggregate planning models. All approaches which were tested showed improved performance over what the firm actually experienced. Future research is seen as developing along two concurrent paths. The first is to expand the scope of aggregate planning models by including more decision variables such as subcontracting, marketing strategies, and capacity planning decisions. The second is to develop more complex and realistic corporate simulation models on which a variety of decision strategies can be tested.

Welam, P., "An Interactive Aggregate Planning Model," paper presented at ORSA/TIMS meeting, November 19, 1975. Las Vegas, Nevada.

For purposes of aggregate production smoothing, quadratic functions often produce good fits to data on some of the relevant incremental costs, such as inventory and overtime costs. However, when costs of hiring and laying off workers are described by smooth quadratic functions, the model solutions tend to involve very frequent minor work force adjustments. For good reasons, production managers are often unwilling to actually implement such decisions. In our model no attempt is made to explicitly model hiring and layoff costs. Instead we suggest an interactive model where through parametric analysis of a set of work force constraints a manager can establish the appropriate trade offs.

MATERIALS HANDLING AND WAREHOUSING MODELS

Cockhill, G. L., M. J. Norman, and D. Seaborn, "Simulation of Warehouse Operations," Paper presented at ORSA conference, October, 1970. Detroit, Michigan.

This paper describes a study of the operations of a large multi-floor consumer goods warehouse, including scheduling, truck and railcar terminal operations, storing, stock ordering and replenishment, and order picking. The design of the data collection experiments is particularly interesting, as the observations necessarily covered many simultaneous activites interfacing (and often competing) with each other. The analysis of data for input to the mathematical/logical model required extensive use of data reduction techniques and an intimate knowledge of the operations being represented. Finally, the experiments performed on the model and some of the recommendations made as a result of the study are presented.

Donaghey, C. E., "A Generalized Materials Handling Simulation Systems," AIIE Transactions, Vol.1, No. 1, March 1969, pp. 11-16.

Describes a simple but universally applicable materials handling simulation system which has been programmed in Fortran by the University of Houston.

Fogarty, D. W. and J. E. Benjamin, "Preliminary Analysis: Materials Management Software Utilization," paper presented at ORSA meeting, May 2, 1975. Chicago, Illinois.

Preliminary results are reported on the findings of a survey of the utilization and effectiveness of commercially available and internally developed materials management software at over 500 manufacturing and distributing organizations. Results include comparative analysis of SIC classification, organization size, utilization of internally and externally developed software, modules developed, program effectiveness, supplier, and program modifications required, and implementation problems using standard nonparametric statistical tests. The questionnaire was designed after a pilot questionnaire was sent to approximately fifty production control and systems managers, mostly members of APICS, who completed the pilot questionnaire and suggested modifications.

Khan, M. U., "A Simulation Model of a Major Assembly Plant Material Handling System," paper presented at ORSA conference, October 28, 1970. Detroit, Michigan.

The purpose of this study is to produce a digital simulation model which can be used to evaluate the capacity of a material handling system in a major and final assembly complex at a given moment (static situation). The primary output is a set of conflict free schedules for moves, bridge cranes and bays, and statistics to evaluate the plant capacity and analyze the work flow in the plant. Inputs to the model are a set of moves, their path and timing, number of bridge crane(s), predecessor, and successors, a desired start time and a plant description.

Markland, R. E., "Analyzing Geographically Discrete Warehousing Networks by Computer Simulation," Decision Sciences, Vol. 4, No. 2, April 1973, pp. 216-31.

This paper describes a comprehensive simulation modeling approach to the problem of locating warehousing facilities in a fashion that minimizes the cost associated with operating a multi-product, multi-source, multi-destination distribution system. The digital simulation model presented in the study is derived within an "industrial dynamics" framework, utilizes input from an existing management information system, and employs a number of relatively simple heuristic procedures to analyze various alternative warehousing networks. Simulation results, in terms of the distribution costs associated with various warehouse locations, are presented for cases involving the effect of provision of a 100% service level, the effect of constraining product availability and/or inventory capacities at various warehouses, and the effect of deleting various warehouses from the existing warehouse network.
(author's abstract)

Ramsing, K. D., and R. M. Stair, Jr., "The Effect of a Capital Investment on an Existing Materials Management System: A Case Study Using Simulation," Proceedings of the Academy of Management, August 11-14, 1976, Kansas City, Mo.

Traditional methods of analysis of capital investment, including "Payback Period," "Internal Rate of Return," and "Present Value" approaches prove to be insufficient for determining the expansion of production facilities. This is largely due to the high degree of interaction of the proposed facility with existing plant and equipment. The method of solution necessitated a complex Monte Carlo simulation model which incorporated inventory facilities and levels, as well as plant and equipment.

(author's abstract) The author presented the following results: "With over two years of simulated outputs, it was evident that the simulation approach provided the answers to the perplexing questions about the impact of the proposed investment on the materials management system. This approach is not a complete substitute for the more traditional methods of analyzing and ranking capital investment proposals, but it does supply the decision maker with vital information not available from the traditional approach."

Thompson, D. F. and J. L. Cnossen, "Simulation Model of a Computer Controlled Automatic Warehouse," Simulation, Vol. 10, No. 6, June 1968, pp. 297-304.

Faced with the problem of designing a computer controlled automatic warehouse, the authors of this paper chose to simulate the operation of the warehouse and then use the simulation to evaluate the operational effects of various system parameters and control policies. The results of each run were analyzed and used to guide selection of warehouse system parameters and control policies for use in the next run. The result was an evolutionary process which led ultimately to a satisfactory design. The authors have demonstrated very well the utility of digital simulation as a tool for designing and evaluating complex systems.

Welch, J. L. and J. M. Starling, "Introduction to Materials Management Simulation Model Building," Journal of Purchasing and Materials Management, Vol. 10, No. 2, May 1974, pp. 48-54.

The authors state that they are presenting a simplified simulation model of the production and distribution functions of a small firm "to demonstrate that managers who have limited knowledge of objective systematic decision making techniques can utilize such tools effectively." This assertion is never actually demonstrated, however, he does provide a reasonable "how to" guide, including flow chart and step-by-step instructions. There is no discussion of model validation or application.

JOB SHOP MODELS

Baker, C. T. and B. P. Dzielinski, "Simulation of a Simplified Job Shop," Management Science, Vol. 6, No. 3, April 1960, pp. 311-23.

This is a report of the results of some digital computer simulation studies of a simplified model of a job shop production process. Such factors as the average effectiveness of schedules under the impact of random variations in processing times and the effect of changing operating policies are considered. The average manufacturing times and predictability of completion times were used as measures of effectiveness.
(author's abstract)

Cantellow, D. G., R. V. Pitt, R. J. Saw, and J. Hough, "Machine Shop Problems: An Operational Research Approach," O. R. Quarterly, Vol. 24, No. 4, pp. 403-525. (no ref)

Production planning and scheduling in batch production environment presents management with many problems, ranging from long term capital investment in machine tools to short term batch sequencing. This paper, which is aimed at the production manager, introduces the general concept of model building and then discusses the more specific technique of computer simulation modelling. A simple example of the latter is used to illustrate the basic properties of such a model and then the actual model currently being used is described. The possible applications of such models are discussed and developed. Finally a case study is presented which shows how the model has been employed in actual production environment.

Freeman, D. R., S. Hoover, and J. Satia, "Machine Interference Simulation Model," paper presented at ORSA/TIMS meeting, November 8, 1972. Atlantic City, New Jersey.

The analytical techniques developed to solve the machine interference problem do not usually suffice due to restrictive assumptions made on machine and operator characteristics. This paper describes the development of a general purpose simulation model and its application to a machine interference situation. The model is designed for M (not necessarily identical) machines and N operators of varying job classifications performing machine tending and/or service tasks. While describing its actual application, particular attention is paid to the analysis of several possible staffing alternatives and other intangible considerations. Finally, the effect of several service disciplines and their implementation is discussed.

Fryer, J. S., "Operating Policies in Multiechelon Dual-Constraint Job Shops," Management Science, Vol. 19, No. 9, May 1973, pp. 1001-12.

In this paper a simulation study to examine the effects of operating policies on the performance of a multiechelon dual-constraint job shop is described. A hypothetical shop in which machines and workers are constrained resources is the setting of the study. The shop consists of divisions comprised of work centers which, in turn, contain machines to which workers are assigned. There are fewer workers than machines. Operating policies consist of rules for dispatching and labor control. There are two levels of labor control-decision rules are used for allocating workers to divisions and then to work centers within divisions. The measure of shop performance are mean flow-time, flow-time variance, and worker tranfers between divisions and work centers.

Labor control decisions prove to be important in their effect on both flow-time and labor transfer measures. In some cases, labor control decisions are more important than dispatching decisions. The effects of dispatching decisions on flow-time measure are consistent with previous job shop research. Dispatching decisions also affect labor transfers.

Fryer, J. S., "Labor Flexibility in Multi-Echelon Dual-Constraint Job Shops," Management Science, Vol. 20, No. 7, March 1974, pp. 1073-80.

This paper is a continuation of the author's previous paper. Simulation of a small job shop is used to study when a worker should be eligible for transfer from a division or work center in a job shop having more machines than workers.

Fryer, John S., "Effects of Shop Size and Labor Flexibility in Labor and Machine Limited Production Systems," Management Science, Vol. 21, No. 5, pp. 507-515.

This paper describes a simulation study that examines the influence of system size and labor flexibility on the performance effects of dispatching and labor control decision rules in labor and machine limited production systems. Four production systems are used-a small job shop, medium job shop, a large job shop in which the worker can be transferred between major organizational divisions, and a large job shop in which the workers cannot be transferred between divisions. For each system the decision rules for dispatching and labor control are varied. Comparisons are made of the relative effects of the decision rules for the different systems on mean flow-time, flow-time variance, and number of worker transfers. Results indicate that the effects of dispatching and labor control decisions rules on flow-time measurements are consistent for different size and labor flexibility combinations. With one exception, the effects on labor transfer measurements are also consistent. Consistency here means that the direction of change in performance measurements are the same for the different systems.

Hyman, M. G., "A Simulation Approach to Optimization of Labor Allocation in an Integrated Circuit Shop," paper presented at ORSA meeting, May 1, 1975. Chicago, Illinois.

A comprehensive labor and machine constrained simulation model of an integrated circuit shop has been developed. The high level of technology employed in the shop results in a labor force which is differentiated into small homogeneously skilled sections. This paper examines two significant problems in the shop. First, determination of the impact of varying degrees of differentiation of the labor force. Second, determination of the optimal number of workers allocated to each section. The cost function for the second problem is formulated as a pseudo-boolean programming problem by simulating each treatment of a properly chosen fractional factorial design.

Jackson, J. R., "Simulation Research on Job-Shop Production," Naval Research Logistics Quarterly, Vol. 4, No. 4, 1957, pp. 287-95.

This is an extremely early paper with nothing of apparent interest to the modern reader. Methodological details are almost entirely absent.

Jaunsen, W. H., "A Simulation Model of a Job Shop with Material Handling and Rework," paper presented at ORSA meeting, October 18, 1974. San Juan, Puerto Rico.

This paper describes a simulation model for a job shop of N work centers, K machines, and M jobs with random arrivals and variable machining times. There are R handling devices which move the jobs in batches of no more than S jobs from one work center to another and return empty. Move and return time are variable. Rework is considered by recycling a percentage of jobs, with a higher priority, from the inspection work center to other selected work centers than other jobs. Statistics collected include machine utilization and time through the job shop, this is presented by histogram.

Pegels, C. C., and P. S. Narayan, "Simulation as a Planning Tool for a Complex Machine Shop," Int. Jr. Prod. Res., Vol. 14, No. 3, May 1976, pp. 387-400.

A deterministic simulation study of a complex machine shop consisting of 69 work centers is presented. The purpose of the simulation study was to develop a planning tool to evaluate the effects on overtime, work center bottlenecks, in process inventory build up, delivery delays, and other output variables caused by individual part delays of different load mixes, modifications in work center capacities, installation of more automated machinery and modifications in scheduling rules. The simulation program and the machine shop and its models are described. It was found that the developed simulation program can be used as a useful planning tool for evaluating short term and intermediate term alternatives.

Trilling, D. R., "Job Shop Simulation of Orders that are Networks," The Journal of Industrial Engineering, Vol. 17, No. 2, Feb. 1966, pp. 59-71.

Shop orders are simulated whose routings or line-ups use varying combinations of parts. The means of coding such routings in order to define the networks they represent is described. The technique of synthesizing these networks is discussed. Special logical problems arising from the handling of such routings within a simulation are indicated, as well as the new measures of performance they necessitate. (author's abstract)

The article describes an early effort at simulation through activity or mode network representation: This work has been superceded by more recent efforts, particularly the GERT series.

PRODUCTION LINE MODELS

Abel, J., "Simulation of a Work Station for Mixed-Model Assembly," paper presented at ORSA/TIMS meeting, November 8, 1972, Atlantic City, New Jersey.

A CALL/360:BASIC Model has been developed and used to simulate a work station on a mixed model assembly line. Six different truck models run on the line. Each truck may require different operations due to a wide variety of optional equipment that each may have.

The computer model is used for performance studies of the present system. It studies the optimal sequence of truck models to be run for obtaining a proper line-balance. The model is also used for long term expansion planning to meet an increase in the number of trucks to be run on the line.

The output from the simulation will be used to determine the physical characteristics of the work station, manpower requirements and truck model sequence to be run on the line.

Baxey, G. M., "Assembly Line Balancing with Multiple Stations," Management Science, Vol. 20, No. 6, Feb. 1974, pp. 1010-21.

A case is stated for extending the techniques of assembly line balancing to provide for the parallel operation of identical stations, where this leads to a reduction in idle time. The practical implications of operating with this type of system are discussed, both for the stations themselves and the line as a whole, with reference to various classifications of assembly lines, and ways in which balancing can be made to fit into an overall strategy for production line design are touched upon. Two distinct types of computer program have been developed to enable multiple stations to become a recognized feature incorporated into "heuristic" line balancing, rather than an appendage to be applied ad hoc by industrial engineers when current techniques have proven inadequate. One approach is based on the more sophisticated version of the "positional weight" method, while the other relies on the contrasting philosphy of the "random generation" method, and a comparison is made of their relative success in solving two assembly line problems and their potential from an industrial viewpoint.

Crisp, R. M. Jr., R. W. Skeith, and J. W. Barnes, "A Simulated Study of Conveyor-Serviced Production Stations," International Journal of Production Research, Vol. 7, No. 4, 1969, pp. 301-09.

Previous research on conveyor policy was based on the assumption that the number of units on a conveyor is a stationary Bernoulli distribution. A GPSS-III simulation program was developed for this research to model the conveyor system. Then the above assumption was tested by means of a runs test. It was found that the assumption is not generally valid when a sequential range policy is used for loading random. Thus the stationary Bernoulli distribution would not hold.

Goldberg, A. J., "Final Report on the Simulation of the Production Run of the Magic Tee at Microwave Development Laboratory," paper presented at ORSA meeting, May 5, 1971. Dallas, Texas.

This report informs how a computer model of the production of the magic tee, a radarscope component, was formulated. Computer simulation in Fortran was used to model the production run so it approximated reality. The analysis focuses on developing a model of the present production setup.

Moberly, L. E. and Wyman, P. F., "An Application of Simulation to the Comparison of Assembly Line Configurations," Decision Sciences, Vol. 4, No. 4, October 1973, pp. 505-16.

At issue in this study is a decision rule for management. Management has the alternatives of constructing two single independent lines or of constructing one dual line at the same cost. It may be possible with dual production lines to have the capability of expediting part through a station that is parallel to a failed station. Expediting is accomplished by having the worker at the failed station assist the worker at the parallel non-failed station: This feature is essentially a different configuration and is called an expedited dual production line. Which of these configurations will give the greatest output rate?

Simscript II was used in the simulation study. The author found that the choice among line configurations was a function of such factors as inter-stage queue capacity, time to repair failed machines, machine failure rate, and number of stations.

Pai, Ashok R., and Keith L. McRoberts, "Simulation Research in Interchangeable Part Manufacturing," Management Science, Vol. 17, No. 12, pp. 732-743.

Simulation is being used to attain a better understanding of many complex situations. In this analysis, GPSS/360 was employed as a simulation language to investigate the effects of operating policy guidelines and decision rules in the manufacturing of component parts used interchangeably in the final product form. The analysis is developed on hypothetical data and interchangeable part mixture based on an actual manufacturing system. A number of criterion measures are considered and four policy decision rules are investigated.

Pim, D. N. and J. M. Bullingham, "Production Line Flow Simulation by Mini Computers," Prod. Engr., Vol. 54, July-Aug. 1975, pp. 413-16.

This article describes a computer program which simulates production line flows. Most of the existing computer programs require large computers and a knowledge of special programming languages. Thus, existing programs are not universally used, and there is a need for easy to use programs.

The program described has been developed for simulating production lines with up to 50 work stations, but it requires only a small 4K, 16 random bit access storage computer.

It enables production managers not only to test proposed line layouts at the drawing boards but also to simulate day to day variations in their lines due to work force, machine failures, etc. The program highlights queues, staff/machines utilizations, and component stocks.

The production line is modeled by a number of interconnected work stations. Each work station can have only one input, but multiple outputs are allowed. Each work station has its queue where jobs waiting to be processed are held.

Prikster, A. A. B.,"Application of Multichannel Queueing Results to the Analysis of Conveyor Systems," The Journal of Industrial Engineering, Vol. 17, No. 1, January 1966, pp. 14-21.

In this application, equations for several performance measures for conveyor systems with no storage and no feedback are developed. In addition, an extension to the case where there is no storage in all but the last channel and infinite storage in the last channel is made. Tables of the performance measures are included for the queueing situations M/G/m and D/M/m, applied to conveyor systems. Recirculation of items is also considered and a simulation program is used to obtain the performance measures associated with the conveyor system.

(author's abstract)

Taylor, B. W., II., and K. R. Davis, "Addressing the Production Balancing Problem," Comp. and Opres. Res., Vol. 3, No. 1, p. 15-26.

The authors have noted that though a lot of research has been done in the field of production balancing, very little has been done of operational significance. The objective of the paper is to present a computerized interactive technique that addresses the problem of balancing a production line. However, the key directive is not to present the technique. Rather, the directive is to demonstrate the behaviorist and change factors can be addressed while achieving a balanced line.

The approach specifically examines production personnel reassignments as a key implementation factor. Some prior research studies identify variable operator performance times as a key factor relating to less than uniform flow ratio and excess inventories.

Tonge, F. M. A Heuristic Program for Assembly Line Balancing. Prentice-Hall, Inc. Englewood Cliffs, N. J. 1966.

Many industrial decisions entail selecting some optimum combination of factors from a space of many possible combinations. Assembly line balancing, job-shop scheduling, personnel, and equipment assignment are examples of this class of combinatorial problems. Mechanization of solution procedures for such problems can (potentially) contribute not only dollar savings through better solutions for the cost, but also intangible returns through much quicker results. A purpose of this research is to explore one approach to such mechanization.

Because no general theory exists for dealing with large scale combinatorial problems, much basic mathematic research in this area has been directed toward developing computational shortcuts and approximations for treating such problems. In fact, the combinatorial problems listed above are members of the class of ill-structured problems-known exhaustive algorithms for their solution require too much computational effort to be feasible.

Our two goals are: (1) to develop an acceptable, though not necessarily optimum, procedure for assembly line balancing, (2) to gain some understanding of the use of computers for implementing heuristic decision procedures in the industrial arrangement area.
(from the author's preface)

Extensive details of the heuristic is provided in Appendix C; however, a program of the heuristic is nowhere provided.

Young, H. H., "Optimization Models for Production Lines," The Journal of Industrial Engineering, Vol. 18, No. 1, January 1967, pp. 70-78.

This article reports on a systems engineering approach to the development of highly efficient production lines, employing the digital computer as an optimizing controller. Production lines are generally favored over job shop production for products which are to be manufactured in large volumes over lengthy periods of time. The production lines may or may not have provision for "buffers" or in-process inventories between production stages, the most common situation is for limited buffers to be present.

The research study was limited to determining the best order to schedule products, the economic batch sizes and the economic buffer capacities and to developing a computer simulated production line to test optimization procedures. The simulation model, written in Fortran IV, was a next-event simulation based on previous models developed by Prikster.

The author concluded that analytical economic buffer size models resulted in unnecessarily high buffer capacities and the simulation model was extended such that economic buffer size was determined by simulation.

NETWORK ANALYSIS; QUEUEING THEORY

Burt, J. M. Jr., D. P. Gaver, and M. Perlas, "Simple Stochastic Networks: Some Problems and Procedures," Naval Research Logistics Quarterly, Vol. 17, No. 4, December 1970, pp. 439-59.

This paper deals with stochastic network problems. The assumption that individual task completion times are fixed and known in advance is unrealistic in a PERT network. Thus, the authors introduce several Monte Carlo simulation techniques to determine the expected project completion time and the distribution of individual task completion times.

Burt, J. M. Jr. and M. B. Garman, "Conditional Monte Carlo: A Simulation Technique for Stochastic Network Analysis," Management Science, Vol. 18, No. 3, November 1971, pp. 207-17.

The concept of conditional Monte Carlo, as applied to stochastic networks, is presented and illustrated with an example. A considerable improvement in the estimates is noted over those obtained using straightforward Monte Carlo. A general procedure for performing conditional Monte Carlo and an algorithm for determining unique activities are also presented.

Chu, K., and T. H. Naylor, "Two Alternative Methods for Simulating Waiting Line Models," The Journal of Industrial Engineering, Vol. 16, No. 6, November-December, 1965, pp. 390-394.

Two models, a fixed time increment model and a variable time increment model, are described for the single-channel, single-station waiting line situation. They are formulated as computer subroutines (in flow chart form) which may be useful (as subroutines) in simulating on a digital computer more complicated waiting line systems. Also presented is a Fortran computer program, which the authors have used in their experimental runs, for generating a negative exponential distribution with a given expected value. (author's abstract)

Fishman, G. S., "Output Analysis for Queueing Simulations," paper presented at ORSA fall conference No. 2, 1972.

This paper presents a method for estimating the variances of sample performance measures in queueing simulations, for removing the bias in these sample measures due to initial conditions and for deriving approximating confidence intervals for the true performance measures. It also describes how a variance reduction can be achieved using the method when comparing performance measures for two queue disciplines. The approach requires only that every time the system passes through the empty and idle condition future behavior is independent of past behavior.

Frank, H., "Estimating Connectivity in Probabilistic Networks," paper presented at ORSA meeting, May 7, 1971. Dallas, Texas.

Evaluating network connectivity for large networks is a formidable problem. Because of the combinational nature of this problem, exact analytical approaches are generally intractable. Consequently, one must resort to heuristics or simulation. In this paper, we give a heuristic method to rapidly compute the approximate probability that a network is connected. The method is applicable to networks with as many as several thousand nodes. In addition, the procedure suggests an efficient simulation scheme making use of variance reduction procedures for improving the accuracy of the approximation.

Heppe, R., "A Method of Simulating Queueing Problems on a Small Computer," paper presented at ORSA meeting, November 10, 1969. Miami, Florida.

Conventional methods of simulating queueing problems, such as are encountered in multicommodity flows through transportation or processing networks, simulating job shop sequencing and scheduling arrangements, etc., require data to be maintained on the status of each item in the system. Large amounts of core memory are required for this approach. A method is presented for performing such simulations by following only one item at a time through the system, accumulating flow data which is then used to obtain an estimate of queueing delays. Reiteration of the process provides improved estimates. Conditions under which the process converges rapidly are discussed.

Jackson, J. R., "Queues with Dynamic Priority Discipline," Management Science, Vol. 8, No. 1, October 1961, pp. 18-34.

This paper reports results of a computer simulation of a queueing system under a dynamic priority discipline which resembles due-date-like priorities. The coding was done in Fortran II and the simulation used approximately 20 hours of 709 time. Conjectures as to the slope of the upper tails of the waiting time distribution are made and examples of the potential application of these conjectures are given. It is interesting that simulation results are given in support of theoretical work.

Riggs, James L. and Michael S. Inoue, "ESP - Economic Scheduling Path - A Network Based Resource Management Tool for Repetitive Projects," Technical Papers, Twenty-Second Institute Conference and Convention - A.I.E.E., Boston, May 12-15, 1971, pp. 321-330.

A network model and an algorithm are presented for optimizing resource utilization in repeated projects. Traditional tools, individually, are inadequate in effectively scheduling a program of repetitive projects. Techniques developed for continuous production are not suitable scheduling tools for complex projects. The ALB algorithms, when available, minimize in process unavoidable delays, but do not necessarily eliminate them. Furthermore, they do not allow for any in process inventory. Thus, industrial engineers are faced with the challenging problem of scheduling continuous utilization of crews for maximum productivity while batch processing individual projects for minimum project durations.

The ESP - Economic Scheduling Path - is a network-based management tool designed to overcome such difficulties through a combination of advantages offered by traditional techniques. It is a "mature organization" tool for scheduling projects and crews simultaneously. It is CPM type representation of a program of projects based on "Remark line" used in Japan. The ESP algorithm guarantees a delay-free schedule for each crew and provides Remark Line Scheduling.

The paper also defines the basic mathematical model and terminology. A new method for quickly developing ESP network from on-arrow-network drawn for a single project is described, followed by the explanation of CSP and ESP time computational procedures using examples.

Wolff, R. W., "Efficient Estimation of High Priority Customer Delay," paper presented at ORSA meeting, October 18, 1974. San Juan, Puerto Rico.

For simple queueing models not involving priorities, it has recently been shown that the asymptotic efficiency of a direct estimator of expected delay is different from that for the delay estimator which multiplies a direct estimator of average queue length by the arrival rate (using "$L=\lambda w$). Results to date favor estimating delay directly. However, the effect diminishes with increasing utilization. This paper presents corresponding analytic results for M/G/1 queues with priorities and empirical results (obtained via simulation) for a more complicated priority queue model of a real system. When high priority customers have a small utilization factor (a common occurrence), the relative efficiency of directly estimating their expected delay can be very large.

MAINTENANCE MODELS

Burling, J. M., "Computer Simulation in Action; Planning Maintenance Manpower Needs," Computer Decision, Vol. 2, No. 2, Feb. 1970, pp. 20-25.

In a manufacturing complex which includes a very large number of different machines, the planning of maintenance schedules is very difficult and even worse to amend if delays occur at some point. A simulation model of unscheduled service requirements allows maintenance to forecast machine availability given a certain manpower level. Normal scheduled maintenance is not included. It allows alternative shift arrangements to be tried out under simulated working conditions so that the best emergency plan can be prepared.

Hardy, S. T. and L. J. Krajewski, "A Simulation of Interactive Maintenance Decisions," Decision Sciences, Vol. 6, No. 1, pp. 92-105.

In this day of automation, effective maintenance decisions are a legitimate concern. This paper broadens the traditional concept of maintenance to include any policies which tend to reduce the frequency or severity of failures. A simulation model is used to demonstrate the interrelatedness of multiple maintenance policies for a truck depot. It is demonstrated that the proper selection of a maintenance policy set should consider the variability of the system output due to the daily dynamics, as well as the transient behavior of the system.

Pritsker, A. A. B., "The Monte Carlo Approach to Setting Maintenance Tolerance Limits," The Journal of Industrial Engineering, Vol. 14, No. 3, May-June 1963, pp. 115-19.

A solution by the Monte Carlo method is proposed to relax the assumption that maintenance action returned the system to "as good as new conditions" and the unit cost of degradation could be represented as a discrete function of the system variable required in an analytical procedure for setting maintenance limits. The criterion factors used are the costs associated with degraded performance and maintenance action over the operation life of the system. It is assumed that a description of the operation of the system is available and the effects of maintenance action are known. Two examples are given and a simplified digital computer program presented.
(author's abstract)

Shaw, L. and S. G. Sinkar, "Redundant Spares Allocation to Reduce Reliability Costs," NRLQ, Vol. 23, No. 2, pp. 179-197.

The problem considered here is the optimal selection of the inventory of spares for a system built from two kinds of modules, the larger of which can be connected so it performs the role of the smaller one. The optimal inventory is the least costly one which achieves a specified probability that the spares will not be exhausted over the design lifetime. For some costs and failure rates, it is most economical to use the larger module for both roles, due to increase in flexibility in the deployment of a single type of spare module. Both analytical and simulation methods have been used to study this problem.

PLANTWIDE MODELS

Farmer, J. A. and R. H. Collcutt, "Experience of Digital Simulations in a Large O. R. Group," in Digital Simulation in Operational Research, S. H. Hollingdale, Ed., American Elsevier Publishing Co., 1967, pp. 166-75.

This article discusses the development and use of digital simulation (on the Manchester MK1) at British Iron and Steel Research Association from 1955 to 1967. Operating experience, simulation dangers and limitations, and requirements of simulation systems are outlined. Also included are interesting tables showing resource requirements experience as a function of model size and control rules, and a listing of simulation models at the subject company. The article centers on MONTECODE and Pegasus AUTOCODE languages and pays scant attention to simulation languages more familiar to readers in the United States.

LeGrande, E., "The Development of a Factory Simulation System Using Actual Operating Data," Management Technology, Vol. 3, No. 1, May 1963, pp. 1-19.

Development of a simulation process for the El Segundo Division of Hughes Aircraft Company is described. For simulation purposes the shop was organized into 115 machine groups and 47 labor classes. The article is nontechnical and consists primarily of a discussion of how simulation can assist job shop management. Results of a dispatch rule study are presented in detail.

Nelson, R. T., "A Simulation of Labor Efficiency and Centralized Assignment in a Production Model," Management Science, Vol. 17, No. 2, October 1970, pp. 97-106.

This paper reports a set of simulation experiments with a service system model in which labor interchange is possible between service centers. It explores design and control aspects of labor and machine limited systems. A simple model with two service centers and two laborers is employed to explore the relationships among three experimental variables. The variables are the efficiency of labor exchange, the degree of centralized control exercised in labor assignment, and the queue discipline. Both series and job-shop type routing are studied.
(author's abstract)

Wright, W. and J. H. C. Scrimgeour, "Modeling Steel Mills on a Digital Computer," Iron and Steel Engineer, Vol. 39, No. 3, March 1962, pp. 121-29.

Though the hot strip mill and the reversing rougher may be individually studied to determine their highest production rating, they must be coordinated to obtain maximum production. The construction of realistic mathematical models, on a computer, greatly reduces the actual experimental rolling which must be done to formulate an optimum rolling schedule.

PLANT LAYOUT; FACILITY PLANNING

Armour, G. C. and E. S. Buffa, "A Heuristic Algorithm and Simulation Approach to Relative Location of Facilities," Management Science, Vol. 9, No. 2, January 1963, pp. 294-309.

This paper give a method for determining relative location patterns for physical facilities. This problem can be formulated as a discrete quadratic programming problem, which, in general, cannot be solved by presently available (1963) computer techniques. The authors have developed a heuristic algorithm which determines what relative location patterns should be altered to obtain sequentially the most improved pattern with each change. They give a computer program which, using this algorithm, causes the change, evaluates the results of the change, and identifies the best relative location patterns. The output consists of a block diagrammatic layout of the facilites area. A manufacturing plant layout example is given. The authors comment that the methodology is general and need not be restricted to such applications.

Carrie, Allan S., "The Layout of Multiproduct Lines," Int. J. of Prod. Research, Vol. 13, No. 6, November 1975, pp. 541-558.

The program considers the layout of multiproduct lines to be an integral part of the production planning system. The multiproduct lines, normally, has three types of moves:

1. In sequence move, from a machine to its immediate neighbor down the line.
2. By pars move, from a machine to a machine two or more places down the line.
3. Backtrack move.

The multiproduct problem can be stated as follows:

> Given a family of parts to be manufactured on a multiproduct line and given the details of the operation sequence, processing times and required quantities determine.
>
> 1. The number of stations in the line.
> 2. Machine type of each station.
> 3. The station at which each operation on each part is to be performed.

DeMaire, J. D., "The Overhead Crane," Industrial Engineering, Vol. 6 No. 3, March 1974, pp. 12-17.

Due to an increase in the production load for a particular casting department, it was decided to increase capacity. However, it was undecided whether the overhead crane system presently in use was adequate given the additional capacity. Simulation was employed to answer this question. This paper discusses the development of the computer simulation model to its successful completion.

Gourley, R. L., "A Modular Utility Simulation Model Used to Test and Analyze Proposed Conveyor Layouts," paper presented at ORSA meeting, October 16, 1974. San Juan, Puerto Rico.

The design of planning of many facilities such as a manufacturing plant or a warehouse may include a conveyor system. A large number of industrial conveyor systems have certain common elements. Many of them run at a constant speed, have discretely spaced hooks or dogs, and recirculate in one or more closed loops. This paper reports an approach to the testing and analysis of this type of conveyor system before it is installed. The approach used is a general purpose simulation model which utilizes a modular format written in GPSS/360. The simulation modules are stacked together in proper order like building blocks to construct the simulation model of a proposed conveyor system.

Hurley, O. R., "Simulation Finds the Best Conveyor Layout," Modern Materials Handling, Vol. 18, No. 10, October 1963, pp. 47-49.

The author reports that simulation of a large manufacturing area of the Hickory, N. C. General Electric plant resulted in improvements over then current management practices in scheduling, predicting bottlenecks, and equipment arrangement. The article is completely non-technical. Although the article might be helpful to the novice who wishes to understand the capabilities of simulation, there is insufficient detail provided for one to determine actual simulation techniques employed.

Lipton, Paul, "Simulation: A Dynamic Tool for Plant Expansion," Ind. Eng., Vol. 1, No. 1, p. 21-25.

This paper discusses a computer simulation model of production system. A new assembly shop was being planned and the simulation model was built to answer the following questions:

1. How much space and man power would be required?
2. Layout of facilities.
3. Whether a particular facility was economically feasible or not.

The model was developed in GPSS and validated.

Misra, P. K. and A. R. Cummings, "Facility Planning: A Plant Simulation," paper presented at ORSA meeting, October 17, 1974. San Juan, Puerto Rico.

A simulation model of a Grocery Product plant is described by banks of extruders, driers, and further processing units, and various packing lines. The production process may be described as follows: various commodities are mixed in batches, extruded, dried, and then through the further processing units, packed off in various pack-lines to yield different products. The simulation model is used to determine the long-term needs as for the number of extruders and number and size of packing units for the purpose of capital budgeting. The paper describes the art of model building, input data requirements, management reports, process of validation, and the implementation results to-date.

Reitman, J., "Design Decisions Through Simulation," IEEE Spectrum, Vol. 11, No. 3, March 1974, pp. 76-79.

The purpose of the article is to describe the use of simulation as a technique for the design of complex, dynamic systems and the technological improvements utilized by Nordes Division of United Aircraft Corporation in practical applications. The article does not go into sufficient detail to be of interest to those experienced in the field.

Marguplis, Kh. Sh., and G. Ya. Fridman, " A Statistical Model of an Industrial Enterprise" (In the Example of a Petroleum Plan), (Russian), Ixvestiya Academica Nauk SSSR Tekhnicheskaya Kibernetica.

In the example of a petroleum processing plant, a statistical simulation model of a complex system is constructed in which the production process and the control process are so closely related that their individual study becomes impossible. The model takes account of perturbations acting on the system. As a formalized scheme describing the system studied a self-adapting (external) system of automatic control is taken. A methodology is developed for simulation of the production processes of continuous type and a more universal principle, as compared to the existing ones, of construction of a simulating algorithm is presented. The proposed model permits solving a collection of problems related to the sphere of planning or long range planning.

Reitman, J. "Simulation of a Manufacturing System," Simulation, Vol. 8, No. 6, June 1967, pp. 311-17.

The article describes the use of GPSS III to model the manufacture of custom-integrated circuits. The model considers sales forecasts, inventory control, and the selection of manufacturing approach. Apparently it was used to study the work flow, inventory policies and internal priorities to be used on a production facility not yet in service. The author claims, "the results from the model agreed with experience when current factors were used as data." As part of the implementation a special feature was added to GPSS to plot the input data. The author feels that graphic presentation of the inputs was quite helpful.

While this article reveals no secrets, it might provide some stimulus to managers not familiar with the possibilities of simulation.

Schmidt, J. W. and R. E. Taylor. Simulation and Analysis of Industrial Systems. Richard D. Irwin, Inc. Homewood, Illinois: 1970.

This book is divided into four sections. Section one discusses probability theory and mathematical modeling. Section two discusses simulation modeling. Section three discusses model validation and analyzes results. Section four discusses the GPSS and SIMSCRIPT simulation languages.

Section one is of no interest to the present project, although it appears to contain concise mathematical reviews of probability and queueing theory, inventory systems and a chapter on reliability, maintenance, and quality control.

Section two begins with a lengthy discussion of the generation of pseudo-random numbers conforming to the uniform distribution over the range (0,1). A Fortran program created by IBM is included. There is, although, a thorough discussion of tests for conformity of the generated numbers to the uniform distribution. There follows a discussion of process generators for a wide range of processes including exponential, gamma, Bernouli, and several others. The chapter on simulation on queueing systems includes discussion of single channel systems and multiple channels in series and in parallel. There is a separate chapter on the simulation of inventory systems.

The book seems to be a good text for the student unfamiliar with the mechanics of simulation, but is too general in nature to be useful in the creation of GEMS.

Smith, W. P. and J. C. Shaw, "Design and Development of a Manufacturing Systems Simulation," The Journal of Industrial Engineering, Vol. 15, No. 4, July-August 1964, pp. 214-20.

This article describes an early simulation model of a manufacturing system using Fortran II and a simple network model. The model apparently does not consider queues. All of this work would seem to be superceded by Q-Gert and other newer approaches.

MISCELLANEOUS

Adelson, R. M., "The Dynamic Behavior of Linear Forecasting and Scheduling Rules, " Operational Research Quarterly, Vol. 17, No. 4, Dec. 1966, pp. 447-62.

In the first section of this paper, some important results of Ward concerning trend-corrected exponential smoothing models are developed and extended. In the second section, a linear production and stock control scheme, in which exponential smoothing is used for forecasting, is examined. Some results analogous to Ward's are obtained for the combined system which throws some interesting light on the interaction between the forecasting and decision making aspects of such a system. (author's abstract)

Ancker, C. J., and A. V. Gafarian, "The Problem of the Initial Transient and the Evaluation of some Proposed Solutions," Paper presented at ORSA/TIMS meeting, April 2, 1976. Philadelphia, Penn.

Two basic problems in digital computer simulation are that of transiency and dependency of observations. Several approaches for dealing with the problem of transiency have appeared in the literature. These have been rules to estimate a point, say in time, where the effects of the starting conditions have essentially "worn off". The bases for some of these rules have been intuitive considerations and for others, the properties of stationary time series. In this study, a systematic evaluation of these rules has been made using the M/M/1 queueing model and a simple autoregressive model of order 1. Also, some new, and what appear to be better rules, have been tested.

Berkowitz, E. N., and R. Semenik, "A Priority Sequence Decision Model of Industrial Purchasing Using Transitional Transaction Simulation," Paper presented at ORSA meeting, October 16, 1974. San Juan, Puerto Rico.

Recent literature in the area of industrial purchasing emphasizes the fact that purchasing agents name their most pressing problem as a lack of time to do their job. The purpose of this model is to provide the industrial purchaser with a decision tool that not only saves time but also increases the efficiency of the industrial purchase. After the decision maker has established minimum requirements that must be met to satisfy the firm's product needs, the computer program will simultaneously evaluate all available sources of supply for the product and indicate the optimum vendor or vendors. At a time when purchasers are more often being called upon to justify acquisitions with hard facts and figures, the model provides this empirical proof. The outstanding feature of the simulation is its flexibility. It does not prescribe the criteria to use for evaluating either the suppliers or the needs of the firm but rather relies on the expertise and judgement of the purchaser to establish the requirements and ratings.

Brightman, H. J. and E. E. Kaczka, "A Computer Simulation Model of an Industrial Work Group," Decision Sciences, Vol. 4, No. 4, October 1973, pp. 471-86.

The paper illustrates the desirability and feasibility of the computer simulation technique in socio-psychological research. Five years of simulated weekly data is used to test several hypotheses which relate the independent variables-supervisory style and worker interpersonal orientation-to productivity, worker job satisfaction and group cohesiveness.

Burgess, A. R. "Comments on 'Simulation in the Application of Wage Incentives to Multiple Machines,'" The Journal of Industrial Engineering, Vol. 13, No. 4, July-August 1962, pp. 264-67.

This is a technical note on an earlier paper by Johnson and Smith (1961). The author's principle contention is that the amount of time for which a machine would be waiting for service was improperly estimated in the original article. He contends that this particular datum can be determined best by incorporating in the simulation model a simple module designed to generate breakdown and repair times and keep track of machine and operator idle times.

Chang, R., D. DeBruin, and B. Hoadley, "Bell System Supply Line Simulation," Paper presented at ORSA meeting, November 12, 1973. San Diego, California.

A general purpose simulation model of the multi-echelon, multi-product Bell System supply line is presented. The object of the simulation is to provide a general tool capable of simultaneously analyzing the interactive effects of various production, repair, junking, stock control and transportation strategies on inventory levels, physical distribution costs and service to the Telephone Companies under both transient and steady state conditions. Questions that are specifically studied via the simulation involve stock centralization, repair line centralization, demand amplification, supply line implication of development decisions, and supply line factors for revenue requirements calculations.

Conway, R. W., "Some Tactical Problems in Simulation Method," Rand Memoranda, October 1962, RM-3244-PR.

A discussion of the problems involved in the actual running of computer simulations. The memorandum considers useful ways of setting up the initial conditions in a simlation model so as to reduce the amount of computer time and to help ensure that valid data are obtained. It also suggests ways of designing experiments with simulation models so that the resulting data from the computer runs will produce valid comparisons among alternative policies or other hypotheses being studied by simulation.

Crane, M. A., "Statistical Interpolation of Simulation Outputs," paper presented at ORSA/TIMS meeting, November 17, 1975. Las Vegas, Nevada.

A method is presented for estimating simulation response surfaces based on simulation runs observed at only a few input parameter settings. Suppose that g is an n-order polynomial output function of an input parameter over some range and that observations are taken at n parameter settings. It is shown that if confidence intervals are obtained for g at the settings then it is also possible to obtain a confidence interval for any input without making any additional runs. Similarly, a simultaneous confidence band may be obtained for the entire function. The technique does not require variance assumptions common in standard regression methods.

Davis, E. A., "A Simulation Model for the Study of Scheduling, Routing and Service Control in Transportation Networks," paper presented at ORSA conference, October, 1970. Detroit, Michigan.

A transportation network simulator has been constructed to provide a quasi-realistic environment within which to test various control algorithms for scheduling, routing and disposition of empty vehicles in a given transportation network serving a time dependent random demand. To facilitate its use in modeling a variety of situations the program is constructed in modular form. A complete simulation program is assembled automatically when the network configuration, control algorithms and input data are specified by the user. A variety of data is collected to aid in assessing system performance.

Dean, S., R. Forsaith, and G. Hvidsten, "A Business Network Simulation System," paper presented at ORSA/TIMS Joint Conference, November 8-16, 1972. Atlantic City, New Jersey.

The authors discuss a generalized procedure to simulate material flow and cost behavior of a complex, process type manufacturing and distribution system. The model is structured as a network. Nodes represent production sites, inventory locations or geographical groupings of both. Streams represent material movement between nodes. Material flows within the network are determined in a logical "top to bottom" sequence from the network output to the network input streams. Costing is then performed by a reciprocal "bottom to top" procedure. The model operates in a conversational mode using a time-shared computer system.

DeLand, E. C., and G. A. Bekey, "Interactive Computer Simulation," Rand Papers, March 1972, P-4791.

Discusses the need for convenient, semi-formal interactive computer simulation tools and the history of their development. A national economy, a metropolis, the ocean, or the human nervous system are too complex to be analyzed effectively except by simulating them. A computer system designed for simulation studies should provide (1) a means for the non-programmer specialist to construct his conceptual model easily and interact with it readily; (2) graphical and nongraphical input; (3) output displays as the solution progresses, enabling the user to intervene as desired; (4) speed commensurate with the user's ability; (5) ease of reentry at any point to alter the model or the conditions and then restart or continue the simulation; (6) convenient information storage, retrieval, and reproduction; and (7) software that handles monotonous details, such as parameter adjustments and warnings of programming problems. Whether present simulation languages can handle biological problems is still uncertain.

Fishman, G. S., "Digital Computer Simulation: The Allocation of Computer Time in Comparing Simulation Experiments," Rand Memoranda, October 1967, RM-5288-1-PR.

An improved step-by-step procedure for minimizing the computer time needed to obtain a specified statistical precision in the comparison of simulation experiments. The simulations are considered as covariance stationary stochastic processes, as explained in RM-4393. Well-known time-saving methods for reducing variance by inducing positive correlations between the experiments and high negative correlations between replications are included in the procedure. Results show that for a given level of accuracy, significantly less computer time is required when sample sizes are determined by the method suggested in the study than when they are equal. Also, small differences in the autocorrelation functions are important when each process is highly correlated. The suggested two-stage procedure provides initial estimates for determining sample sizes and final estimates for testing hypotheses. Graphical analysis suggests that the efficient allocation is not very sensitive to small errors in the estimates of population parameters.

Fishman, G. S., and P. J. Kiviat, "Digital Computer Simulation: Statistical Considerations," Rand Memoranda, November 1967, RM-5387-PR.

A discussion of the statistical problems that arise in computer simulation experiments. Three problem areas inherent in all stochastic system simulation models are discussed: verification, which determines whether a model actually behaves as an experimenter assumes it does; validation, which tests whether the model reasonably approximates a real system; and problem analysis, which seeks to ensure proper execution of a simulation and proper handling of its results. The study traces the elements of a simulation experiment from initial conception to analysis of final results, defining the statistical problems that arise at each step and relating them to the formal body of statistical theory. Since the aim is to promote awareness of problems, not to solve them, the study offers no general solutions but provides references germane to the statistical problems described.

Gaither, N., "The Adoption of Operations Research Techniques by Manufacturing Organizations," Decision Sciences, Vol. 6, No. 4, October 1975, pp. 797-813.

The author reports finding very little present use of simulation (other OR techniques were also reported on) among the 275 firms which responded to his survey. Of the respondents, 142 firms reported using no OR techniques at all. Some of the manufacturing problems possibly pertinent to GEMS and the number of firms which presently apply simulation analysis to these problems are listed below:

PROBLEM	SIMULATION USERS
Production Planning and Control	25
Inventory Control	29
Maintenance Planning	5
Capacity Allocation	13
Material Allocation	14
Line Balancing	6
Logistics Studies	5
Holding Area Sign	6
Waiting Lines	3
Facilities Layout	3

Garman, M. B., "Statistical Techniques in Digital Simulation: The State of the Art," paper presented at ORSA meeting, April 30, 1975. Chicago, Illinois.

Most digital simulations have inherent elements of randomness. When such simulations are employed as models, a variety of statistical techniques are thus useful and necessary in exploring their model implications. Indeed, were we to survey all the simulation uses of statistics we should have to include virtually all of the field of statistics itself. Instead, this paper focuses only on those statistical techniques that are peculiar to digital simulation. The developments in this restricted domain are dichotomized as (1) techniques to artificially control randomness, and (2) special estimators. A survey of recent progress in each category is provided.

Gess, L. E., V. M. Heier, and G. L. Berosik, eds. Record of Proceedings: The Ninth Annual Simulation Symposium.

There were no articles on manufacturing simulation presented at the ninth symposium. One article on an engineering scheduling model deals with a problem similar to that of machine scheduling, however, the chief difficulty encountered in this model was "dealing with the subtle and unquantifiable differences between the skills of engineers." There is also one article on interactive simulation, but it contained no discussion of the techniques employed in the interactive portion of the model.

Green, T. B., W. B. Newsom, and S. R. Jones, "A Survey of the Application of Quantitative Techniques to Production/Operations Management in Large Corporations," Proceedings of the Academy of Management, August 11-14, 1976, Kansas City, Mo.

This paper presents the results of a survey designed to reveal various aspects about the application of nineteen different quantitative techniques to the production/operations management area in the Fortune 500 company. Some of the more pertinent results are summarized in the table below.

	Value of Quantitative Technique					
Quantitative Technique	Unfamiliar with Technique	No Value	Little Value	Moderate Value	Frequent Value	Extensive Value
Simulation	15	34	19	13	12	7
Queueing	25	42	20	8	2	5
Network Analysis	2	35	20	22	14	8
Markov Chain	68	16	14	2	0	0
Inventory Models	10	9	16	16	22	29
Linear Programming	3	35	20	21	10	15

Grossman, M. and S. Prascow, "A Practical Approach to the Modeling of Interactions in Probabilistics Simulation," paper presented at ORSA/TIMS meeting, November 8, 1972. Atlantic City, New Jersey.

This paper demonstrates the practical construction of a joint distribution function of any two random variables that are thought to be correlated. A measure of association is described and shown to have a substantial effect on the results of two different types of probabilistic investment analysis models. An experimental process of determining the measure of association from a series of operational questions presented to management is given. The reaction of management to the capability of correlating variables that had previously been treated as independent by the simulation as described.

Hallam, S. F., et. al., "Implementation of Selected Applications of Simulations in Business," Data Management, Vol. 13, December 1975, pp. 16-21.

This is the sixth and final article in a series designed to help managers understand and apply computer simulation techniques. Previous articles in Data Management defined simulation (February 1975), illustrated the steps in the simulation process (April 1975), suggested various ways to manage the simulation project team (June 1975) provided guidelines for successful construction of simulation models (August 1975) and described the validation process (October 1975).

This article discusses how simulation may be used to aid the decision maker in the areas of inventory control, production scheduling and marketing. The discussion is very general and would be of interest to those considering the implementation of a simulation model and possessing little knowledge of its uses.

Hopeman, R. J., Systems Analysis and Operations Management, Charles E. Merrill Publishing Co., Columbus, Ohio, 1969.

Hopeman has separate chapters on inventory planning and control, forecasting materials requirements, order quantity and reorder point decisions, and the logistics subsystem. Within his chapter on the logistics subsystem are brief, introductory sections on queueing theory and Monte Carlo techniques.

Hosford, J. E., "Simulation by Incremental Stochastic Transition Matrices (SISTM)," paper presented at ORSA meeting, November 10, 1969. Miami, Florida.

Simulation by Incremental Stochastic Transition Matrices (SISTM) is a direct probabilistic simulation technique applicable to most queueing systems. SISTM uses a state vector giving the probability, for each queue, that the queue has X units waiting for service (X = 0, 1, 2, 3,···). This state vector is updated every time increment by multiplying it by a transition matrix giving the probability that the queue length changes from X to X' units. SISTM can change the arrival and service distribution every time increment, can use any discrete service time distribution, and can be used to evaluate systems which have sequential and parallel queues.

Johnson, H. J. and S. S. Smith, "Simulation in the Application of Wage Incentives to Multiple Machines," The Journal of Industrial Engineering, Vol. 12, No. 16, November-December 1961, pp. 428-30.

This paper describes how simulation was used in establishing incentives, standard times, and machine assignments at one plant. Simulation of various operator-machine combinations was used rather than actual observation in order to lower the timestudy observer requirements and also to reduce plant disruption: The author concedes that many of the results "could have been more easily obtained by other techniques of statistics and probability." However, he argued that simulation is easier for timestudy personnel to understand and that it proved to be "direct, convincing, flexible, quick, and effective."

Johri, H. P., P. M. Reilly, and L. H. Brockhoven, "A Stochastic Simulation Model of a Chemical Plant," Infor., Vol. 9, No. 3, November, 1971, pp. 220-29.

A chemical plant, operated batchwise or continuously, is usually complex to control since it involves interaction of various manufacturing units used in the process. The paper describes a simulation study which was used to gain a proper understanding of the plant. The beneficial results obtained from this study include estimation of the long term behavior of the plant, detecting bottlenecks in production train, evaluation of alternative investment strategies for removing bottlenecks, and improvement of operations planning.

Kennedy, W. J., "Recent Advances in Techniques for Generating Pseudo-Random Numbers," paper presented at ORSA/TIMS meeting, November 19, 1975. Las Vegas, Nevada.

Results obtained during investigation of the characteristis of several different Generalized Feedback Shift Register generators are discussed. This type of generator seems to be the best available for use in multivariate applications.

Lane, R. W. and H. M. Donaldson, "Simulation Analysis of a Mechanized Flat Sorting System," Proceedings of 1975 Spring Annual CNF, Washington D. C. A-IEE, Vol. 26, May 20-23, 1975, pp. 324-333.

This paper describes a simulation model which was developed to evaluate a mechanized 'flat sorting system' for the U. S. Postal service. The system of interest consists of an induction function, a storage function, and an output function which for a given sorting scheme, must operate in one of three modes: scheme initializations or non-steady state, steady state and scheme phase-out. For analysis, this flat sorting configuration is categorized as three multi-server queueing systems in series. A fixed time increment model and two variable time increment models are employed to depict the sorter's performance in its three operational modes, after which an example illustrates the model's applications.

Lave, R. E., Jr. "Timekeeping for Simulation," The Journal of Industrial Engineering, Vol. 18, No. 7, July, 1967, pp. 389-94.

This article discusses methods of timekeeping for computer simulation. Timekeeping is thought of as two functions, that of advancing time or updating the time status of entities and that of storing or listing events in the computer. There are descriptions of timekeeping by incrementation and by the event step method. In addition, three methods of listing, the Time Status record, entity, and Time Increment Listing, are described, two of which can be used for an additional method of updating. The three mehtods of timekeeping are compared on the basis of precision and accuracy, run time, and computer storage required. (author's abstract)

Law, A., "Indirect Estimators for Simulated Queueing Systems," Paper presented at ORSA meeting, October 18, 1974. San Juan, Puerto Rico.

This paper is concerned with the efficient estimation of mean delay in queue, d, mean wait in system, w, time average number in queue, Q, time average number in system, L, and time average amount of work in system, E(V). For a certain class of queueing systems, it is shown to be more efficient to indirectly estimate w, Q, L, and E(V) from an estimate of d, than to estimate them directly. These results are empirically verified for a much larger class. In addition, the theory of random walks is used to produce a computationally efficient procedure for simulating GI/G/s queues.

Lewis, P. A. W. and A. S. Goodman, "Statistical Estimation of Large Numbers of Percentiles in Simulations," paper presented at ORSA meeting, May 7, 1971. Dallas, Texas.

Estimates of percentiles of distribution functions, e.g., of a waiting-time distribution studied by simulation, are frequently based on order statistics from a random example of size n. To obtain this sample requires a computer time approximately proportional to n log n, and a block of memory approximately proportional to n. Alternatively estimates based on simple stochastic approximation schemes require times proportional to n and a small, fixed, number of memory locations. This paper treats procedures based on <u>combinations</u> of these estimation schemes that are suitable when many percentiles are to be estimated simultaneously.

Madansky, A., "Optimal Initial Conditions for a Simulation Problem," paper presented at ORSA meeting, October 18, 1974. San Juan, Puerto Rico.

Suppose one simulates an M/M/1 queue and uses the average number (across N replications of the simulation) in the queue at run-end T to estimate the steady-state mean number in the queue. It is shown that the optimal (i.e., mean-square error minimizing) initial condition for the simulation is, for sufficiently large T, to put nothing in the queue. The tradeoff between N and T given this initial condition is also considered.

Manmmel, J. S. III, "Do's and Don'ts of Computer Models for Planning," Harvard Business Review, Vol. 52, No. 2, March-April 1974, pp. 110-23.

In spite of their important advantages, computer planning models have been misused or under-utilized by management. Evidence indicates that the problems are more managerial than technical. The guidelines presented for line managers and planners provide the basis for deciding whether to use computer models as part of the planning process.

Markowitz, H. M., "The Simulation/Information System Interface," paper presented at ORSA meeting, May 9, 1973. Milwaukee, Wisconsin.

Measured by number of applications, simulation has advanced greatly since the introduction of simulation languages over a decade ago. As a percent of its potential applicability to decision making, however, digital simulation is still "rarely used." This situation presumably could be improved by further advances in simulation techniques and training. In large part, however, the day to day neglect of simulation analysis is due to: (a) the very backward state of information system programming (almost comparable to simulation programming in 1960), and (b) the consequent backward state of the simulation/ information system interface. Proposals concerning (a) and (b) will be sketched.

Marien, E. J. and T. H. Gillespie, "Decision Criteria for Continuous versus Discrete Simulation," paper presented at ORSA/TIMS meeting, November 8, 1972. Atlantic City, New Jersey.

As a result of a survey of the literature and the authors' personal experiences with the application of continuous and discrete simulation in marketing, distribution and finance, this paper identifies a set of criteria for determining the essential structure for simulating a specified business system. The paper initially addresses itself to the definition of continuous versus discrete simulation. From this definitional base, the types of problems that are conducive to either discrete and/or continuous simulation are analyzed. The analysis results in the set of selection criteria. Simulation languages that are appropriate for either simulation structure are identified.

Mihram, G., "Simulation, Statistics, and the Systemic Sciences, paper presented at ORSA/TIMS meeting, April 2, 1976. Philadelphia, Pennsylvania.

The paper shows that, among the modeling formats available to operational researchers and management scientists, the one ideally suited to a scientific dissolution of the complexities of the ecologico-environmental, neuro-psychological, medico-systemic, or socio-politico-economic systems is the dynamic, stochastic, and computerized simulation. Being a generator of a randomly selected realization from a multiple time series, such a simulation requires both the application of extant statistical methodology and the development of statistical procedures. The paper reviews the state of the art, delineating the paths yet to be travelled to qualify simulation as the methodology for the scientist of systems.

Nelson, Robert T., "A Simulation of Labor Efficiency and Centralized Assignment in a Production Model," Management Science, Vol. 17, No. 2, p. 97.

The paper reports a set of simulation experiments with a job-shop type production system having a mobile labor force. The experiments reported are based upon a general model of labor and machine limited production systems. The paper extends an earlier work to concentrate on two specific factors of system control; labor efficiency and the degree of centralized labor assignment control. The specific version of the general model used in the experiments have two service centers consisting of two machines each, and two laborers.

Norton, S. and B. M. Schaefer, "A New Method of Discrete System Simulation: Schedule Independent Simulation," paper presented at ORSA meeting, April 30, 1975. Chicago, Illinois.

A new method of discrete system simulation is presented, in which the events in the simulated system are not executed in their real time order of occurrence. An explicit mathematical model expressed in terms of recursive functions is developed to yield a minimum state space representation of the system. This technique enables a more efficient simulation algorithm than conventional event scheduling and process interaction methods.

Okraski, H. and W. Parrish, "Acquisition Cost Estimating Using Simulation," paper presented at ORSA meeting, November 19, 1975. Las Vegas, Nevada.

Acquisition cost estimates developed as single point values are, at best, misleading and, at worst, impossible to achieve. Single point estimates do not sufficiently reflect the assumptions, judgement or apprehensions of the estimator. This paper deals with a technique for incorporating uncertainty and risk into the acquisition cost estimating procedure such that the estimates are presented as a range of values, encompassing engineering, manufacturing and logistic support estimates. The cost estimating model, a pragmatic application of simulation and classical cost estimating procedures, has been programmed in BASIC and is generalizable and exportable.

Oldfather, P. M., A. S. Ginsberg, and H. M. Markowitz, "Programming by Questinnaire: How to Construct a Program Generator," Rand Memorandum, November 1966, RM-5129-PR.

A reference manual for the programming-by-questionnaire technique, presented in sufficient detail to enable a programmer to construct a program generator. Familiarity with the contents of RM-4460 would be helpful to the user, and a knowledge of SIMSCRIPT is mandatory. The forms, use, and operation of the four components of the program generator are described in detail. A summary of technical details and complete editor program listing are included as appendixes.

Oldfather, P. M., A. S. Ginsberg, P. L. Love, and H. M. Markowitz, "Programming by Questionnaire: The Job Shop Simulation Program Generator," Rand Memorandum, July 1967, RM-5162-PR.

A description of the Job Shop Simulation Program Generator, an application of the Programming by Questionnaire technique developed at RAND to reduce the cost and time required to produce large computer programs, particularly those required for simulations of portions of the Air Force logistics system. The user can obtain a computer program by filling out a multiple-choice questionnaire covering aspects of the job shop he wishes to simulate. Answers are punched on seven cards that are fed to the program generator, which checks the answers for consistency, generates the program, and produces the data specifications. The user then completes the data deck according to the specifications, adds it to the end of the program deck, and submits the entire program to the computer. The output consists of interim reports on resource utilization, job statistics, and queue statistics, and a final summary report. The functions of the various routines and the meaning of the variables in the SIMSCRIPT definition deck are given for the use of SIMSCRIPT programmers.

Schmidt, J. W. and R. E. Taylor, "System Optimization Through Simulation," paper presented at ORSA conference, October 28, 1970. Detroit, Michigan.

This paper deals with the optimization of systems based upon a single measure of system performance which is evaluated through simulation. Two optimization techniques are considered; the one-at-a-time or sectioning method and the method of successive quadratic approximations. Experimental designs appropriate to each of these optimum seeking techniques are discussed. These designs are based upon acceptable alpha and beta errors specified by the user. Criteria which may be used to terminate the search for the optimum are discussed and illustrated, including one which attempts to balance the cost of further iterations of the search against the potential gain which may results from continuation of the search.

Shubik, M., and G. D. Brewer, "Questionnaire--Models, Computer Machine Simulations, Games and Studies," Rand Papers, July 1971, P-4672.

A detailed questionnaire intended to aid the designers and users of operational games and simulations in describing, characterizing, and analyzing models, simulations, or games (MSGs). Because the preponderance of such MSGs are supported by the Department of Defense, the questionnaire reflects that emphasis, but is believed to contain a core of more widely applicable information. Since there is no clear agreement on fundamental terms, the authors define gaming, war gaming, simulation, computer simulation, model, MSG, and other terms, and provide explanations for each multiple-choice question. Major sections inquire into MSG purposes, production, cost to produce and to operate, transferability, characteristics and description, validation, documentation, technical coordination, and standards; questions pertaining specifically to manual and man-machine games and simulations are grouped together, and include "unstated purposes" affecting players. A voluntary assessment is requested at the end.

Shycon, H. N., and R. B. Maffei, "Simulation-Tool for Better Distribution," Harvard Business Review, Vol. 38, No.6, Nov.-Dec. 1960, pp. 65-75.

This article describes, in the words of the authors, "the way we applied simulation to solve, to a considerable extent, [H. J. Heinz Company's] distribution problems." Questions to be answered by the simulation were:

How many warehouses should we have?

Where should the warehouses be located?

What customers should each warehouse service?

What volume should each warehouse handle?

How can we best organize our entire distribution function?

The article explains, in non-technical terminology, how simulation works and the data required for this type of simulation.

Slack, Nigel D. and Ray Wild, "Production Flow Line and 'Collective' Working-A Comparison," Int. J. Prod. Res., Vol. 13, No. 4, July 1975, pp. 411-418.

This paper compares the two approaches to mass production of relatively complex discrete items, namely production flow lines and 'collective working.' Even though there had been a lot criticism of certain aspects of the production flow lines, it's still in widespread use. Recently this criticism has attained new proportions and people have started looking at alternative means.

The paper briefly defines the two approaches and discusses the simulation study for comparing the two approaches on various systems. The program was written in Fortran but no characteristics of the program have been mentioned.

Sohnle, R. C., J. Tartar, and J. R. Sampson, "Requirements for Interactive Simulation Systems," Simulation, Vol. 20, No. 5, May 1973, pp. 145-152.

The evolution of computer hardware and operating systems has made feasible simulation research which benefits from the many advantages of computing in an interactive environment. A general discussion of modeling considerations and features of discrete simulation systems is followed by a set of basic requirements for interactive simulation languages and monitors. Systems designed for simulation of particular classes of models are briefly contrasted with more general purpose systems with respect to flexibility, efficiency, and interactive operation. The interactive capability of the language and the communicative function of the monitor emphasizes the importance of coordinated design of these elements. To illustrate the principles presented, cell-space modeling has been demonstrated.

Sussman, J. M. and M. A. Turnquist, "A Bayesian Approach to the Design of Simulation Experiments," paper presented at ORSA/ TIMS meeting, November 17, 1975. Las Vegas, Nevada.

This paper examines several characteristics of simulation as an experimental environment, including: reproducibility, controllability and advantages for relative comparison of alternatives. An approach to the design of simulation experiments is then proposed, based on the use of statistical decision theory. This approach is designed to make effective use of the unique experimental environment offered by simulation, and to allow the analyst to focus his experimentation in such a way as to obtain effectively the information he most needs. Comparison of the decision - theoretic approach with previously existing methods, both analysis of variance techniques and simulation - specific techniques, illustrates several advantages offered by this new formulation.

Tuggle, F. D. and F. H. Barron, "On Judging Computer Simulation Models of Decision-Making Under Uncertainty," paper presented at ORSA meeting, October 16, 1974. San Juan, Puerto Rico.

Difficulties in judging the descriptive adequacy of computer simulation models of decision making under uncertainty are examined in reference to a particular model. Tests of descriptive adequacy are seen to be dependent on the theory implicit in the test. Two basic validation methods are considered--a process method and Turing's test. Having argued that process validation is necessary for face validity, the process method considers both qualitative and quantitative aspects of individual processes. Turing's test judges the similarity of actual decision protocols and model-produced (both simulation and decision-theoretic) protocols. Judges are unable to distinguish actual and simulated protocols, although decision-theoretic protocols are easily distinguished.

Waki, P. N., "Difficult Decisions Made Easy Through Interactive Games," Computer Decisions, Vol. 4, No. 12, December 1972, pp. 18-21.

The author explains the manner by which groups of trainee managers can undertake complex activities in a variety of management environments and situations. An elaborate management game has been programmed in APL, and the article provides details both of the composition and scope of the simulation, and of the interactive methods by which a team of players can input decisions and receive realistic reports and other feedback.

Three firms, each making two products, distributed in three marketing regions, are in competition. The teams are required to make finance, marketing and production decisions concerning their companies.

Zoutendijk, G., "The Impact of Technology on Decision Making," Computers and Operations Research, Vol. 1, No. 1, March 1974, pp. 9-13.

In order to insure that the computer processing and decision aiding models are not delegated to the analyst and computer specialists decision-making roles not intended, there must be more control, independent reviews, and involvement of the decision maker in the models and computer programs. Without those in authority being aware of the assumptions, the structure of the models and the resulting implications, decisions can be unduly influenced, made erroneous or irrelevant or information can be misused. Safeguards and checks and balances must be restored to a level equivalent to that under the previous manual administrative process.